BIOFILTRATION ENHANCEMENT FOR THE TREATMENT OF HIGHWAY STORMWATER RUNOFF

A Thesis
Presented to
The Academic Faculty

By

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In Partial Fulfillment
Of the Requirements for the Degree
Master of Science in Environmental Engineering in the
School of Civil and Environmental Engineering

Georgia Institute of Technology
December 2014

BIOFILTRATION ENHANCEMENT FOR THE TREATMENT OF HIGHWAY STORMWATER RUNOFF

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Date Approved: November 24, 2014

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my advisor, Dr. Susan Burns, for her inspiration and guidance in pursuing this work. The ability to formulate and execute this project has been an invaluable experience that I would not have been able to do without her. I would also like to thank the committee, Dr. Spyros Pavlostathis and Dr. John Koon for their unending support throughout my time at Georgia Tech.

I would like to thank the Georgia Department of Transportation, especially Mr. Jon Griffith, for providing the opportunity for this research and the supporting its growth.

I would like to thank the Geoenvironmental group, especially Kip Gray, Randy Pettyjohn, Xenia Wirth, and Kasey Henneman. I am incredibly grateful for their help with construction of the project during the cold of winter, collecting samples in the heat of summer, and assisting in the lab in countless ways. I could not have asked for a better group to work with and I only hope I can return the favor.

I would like to thank the Civil and Environmental Engineering staff especially Lisa Tuttle, Crystal Hanson, Jeremy Mitchell, Donny Otwell, and Andy Udell for their patience, encouragement, knowledge, and imagination in creating new solutions to the problems I encountered.

I would like to thank my parents, Gary and Therese, and my siblings, Maria and Bobby, for supporting me in all of my endeavors and lending their time and tools to constructing experiments for this project.

Lastly, I would like to thank Daniel Stuhr for always providing joy and laughter when it is sometimes hard to find. I am beyond thankful for the hardware store runs, weekends at the greenhouse, and everything in between.

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LIST OF SYMBOLS AND ABBREVIATIONS

BMP	Best Management Practice
FHWA	Federal Highway Administration
GDOT	Georgia Department of Transportation
hp	horsepower
L/min	liters per minute
LID	Low Impact Design
LOI	Loss on Ignition
m^2/g	square meters per gram
mg/L	milligrams per liter
mg N/L	milligrams of nitrogen per liter
mg P/L	milligrams of phosphorus per liter
NO_3^-	Nitrate
NO_2^-	Nitrite
NO_x	Combined Nitrate and Nitrite
NH_4^+	Ammonium
N_2	Nitrogen Gas
PVC	Polyvinyl chloride
rpm	rotations per minute
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TSS	Total Suspended Solids

SUMMARY

Highway stormwater runoff contains a number of contaminants including nutrients and heavy metals that can be detrimental to the health of lakes, rivers, and streams. Biofiltration is a common stormwater treatment mechanism that can reduce nutrients and heavy metals through physical, chemical, and biological processes. Vegetation type has been shown to impact the removal of nutrients from stormwater runoff (Barrett et al. 2013; Read et al. 2008). The inclusion of a permanent saturated layer underneath the surface of a biofilter has been investigated to enhance denitrification and thus nitrogen removal (Kim et al. 2003; Zinger et al. 2007). Six Georgia native grasses as well as one turf grass have been tested in a column study along with a permanent saturated zone for biofiltration enhancement. Synthetic stormwater was used in this study. Two months of dosages with an average synthetic stormwater were monitored followed by one event with a heavy metal spiked synthetic stormwater, one event with a nutrient spiked synthetic stormwater, and one event with an average synthetic stormwater after two weeks of drought conditions. Biomass fly ash was also added to columns to determine potential benefits to biofiltration applications.

Results indicated that Big Bluestem, Indiangrass, and Switchgrass when paired with a permanent saturated zone remove the highest percentage of total nitrogen across all experiments (4%, 13%, and 18% respectively). These species contained think and dense root systems that spanned the entirety of the biofilter column. Removal of nitrate was enhanced with a saturated zone while ammonium removal decreased. Nitrogen leaching from the columns may be reduced by utilizing soil of low organic content.

Phosphorus, copper, lead, and zinc removal was not correlated with plant species; however, a permanent saturated zone increased removal of phosphorus, copper, and zinc (removal of lead was >97% in all cases making differences in removal insignificant).

These results support the impact of specific vegetation types on the removal extent of total nitrogen. Saturation provided benefits of total nitrogen, phosphorus, copper, and zinc removal in terms of removal extents as well as consistency of treatment across all experiments. Field experimentation is encouraged to determine long term effects at a large scale.

CHAPTER 1

INTRODUCTION

When rain falls on a paved surface such as a highway, the resulting stormwater runoff accumulates a number of contaminants, including oil and grease, nutrients, metals, and suspended solids. Because the source contamination is distributed, it makes highway stormwater runoff a non-point source of pollution for lakes, rivers, and streams (US EPA 2003). Reduction in these contaminants, specifically nitrogen and phosphorus, is often necessary to prevent overgrowth of algae and thus eutrophication of these water bodies. Control of the influx of water volumes during a storm event is also required to protect from erosion. These goals are achieved through the use of best management practices (BMPs). BMPs include infrastructure such as ponds, wetlands, biofilters, sand filers, infiltration trenches, grass channels, and pervious pavements. As the world trends toward sustainable infrastructure initiatives, there is a growing interest in management of stormwater through low impact design (LID), such as biofiltration.

Biofilters (also known as bioretention areas or rain gardens) are highly flexible in application as they can be applied in residential areas, roadway medians, and other urban environments of varying size. Another major benefit to biofiltration usage is the reduced maintenance burden. Vegetation used in a biofilter consists of native grasses, shrubs, and trees that require maintenance 1-2 times per year, as opposed to many turf grasses, which require mowing every 2-3 months after initial establishment. The incorporation of numerous plant species also creates a more aesthetically pleasing environment.

Biofilter Design

Biofiltration design typically consists of a gravel underdrain system, soil media layers, mulch, and vegetation (Figure 1). The design may also include an impermeable liner between the BMP and the native soil in order to retain water in the system or be designed to be in contact with native soil to promote infiltration.

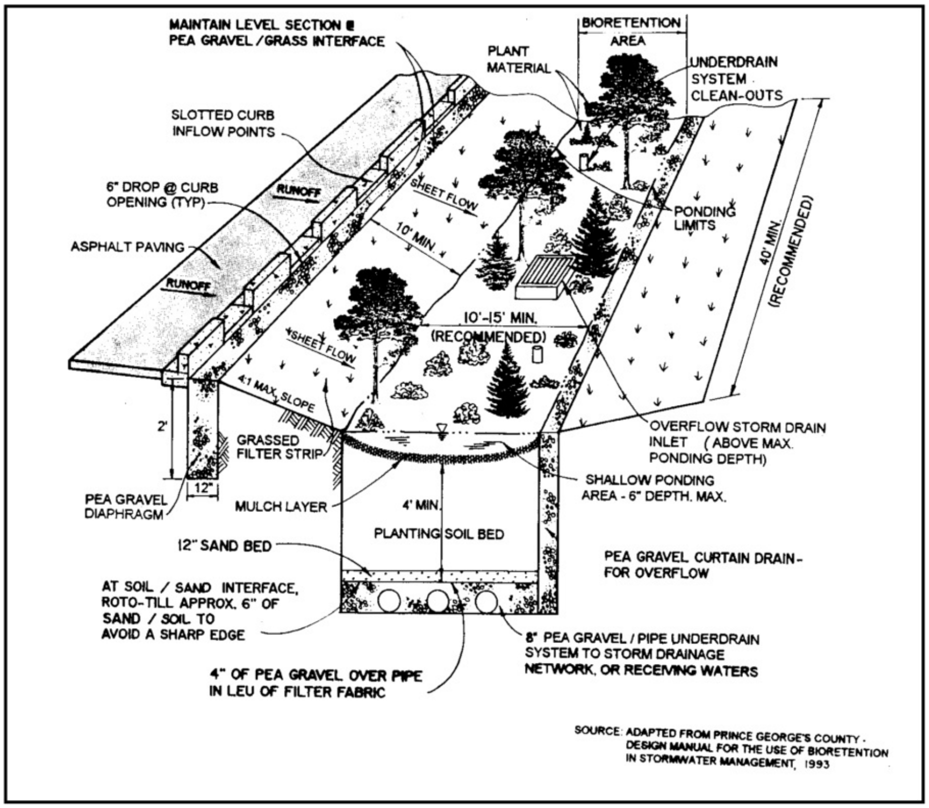

Figure 1: Typical biofiltration design (AMEC Earth and Environmental et al. 2001).

Pollutant removal in biofiltration devices is facilitated by a number of physical, chemical, and biological processes. For example, vegetation enhances the biological activity in the soil, thus increasing pollutant removal when compared to that of a typical sand filter (Table 1).

Table 1: Pollutant Removal Specifications (AMEC Earth and Environmental et al. 2001)

Contaminant	Biofilter (% Removal)	Sand Filter (% Removal)
Suspended Solids	80	80
Total Phosphorus	60	50
Total Nitrogen	50	25
Heavy Metals	80	50

Typical recommendations for biofiltration construction indicate that a variety of warm season and cool season species should be planted to encourage year-round growth and consistent performance (AMEC Earth and Environmental et al. 2001; Department of Water and Swan River Trust 2007). Species should also be tolerant of flood and drought conditions to prevent frequent replanting. Wetland species may also be considered based on the site characteristics (WEF et al. 2012).

Enhancements

According to the Prince George's County Bioretention Manual (2007), removal processes for pollutants include interception, infiltration, settling, evaporation, filtration, absorption, transpiration, evapotranspiration, assimilation, and adsorption. Within adsorption, processes include nitrification, denitrification, volatilization, thermal attenuation, degradation, and decomposition. With this large number of processes and the interactions among them, there are many ways to enhance the treatment capabilities of a biofiltration system. Possible enhancements include the selection of nutrient efficient vegetation, implementation of a saturated layer underground by raising the outlet of the underdrains, and engineering the soil media for maximum pollutant uptake. Evaluation of nutrient efficient species and the inclusion of a saturated zone will be explored further in this study.

CHAPTER 2

LITERATURE REVIEW

Role of Vegetation

Numerous studies confirm that vegetated filters achieve higher removals of nutrients when compared to non-vegetated filters (Bratieres et al. 2008; Davis et al. 2001; Glaister et al. 2014; Henderson et al. 2007; Lucas and Greenway 2008; Read et al. 2008). Nutrients, particularly nitrogen, may be leached by non-vegetated soil based filters because vegetation is not available to utilize the nutrients released from the breakdown of soil organic matter (Hatt et al. 2007). Vegetation also helps to maintain the hydraulic conductivity of biofilters over time (Hatt et al. 2009), and a thicker root morphology may decrease the impact of clogging (Le Coustumer et al. 2012).

An extensive study of 20 different Australian native grasses adapted to low nutrient concentrations in native soils determined that grasses vary greatly in their ability to uptake nitrogen and phosphorus (Read et al. 2008). From this study, *Carex appressa* (Tall Sedge) seemed to be the most effective plant in biofilters, possibly due to the extensive network of fine root hairs which increase the surface area for nutrient uptake. In a follow up study, strong correlations were found between nitrogen and phosphorus removal and the length of longest root, root soil depth, root mass, percent root mass, and total root length (Read et al. 2010). A study in Austin, Texas confirmed this result comparing a common native grass, *Muhlenbergia lindheimeri* (Big Muhly) with a turf grass, *Buchloe dactyloides* (Buffolograss 609). The study demonstrated that biofilter columns planted with Big Muhly consistently performed better than those without vegetation or those planted with Buffolograss (Barrett et al. 2013).

The presence of vegetation has been linked with an order of magnitude increase in nitrification and denitrification 16S rDNA gene concentrations in soil cores. This indicated a greater potential for nitrogen transformations and removal (Chen et al. 2013). This study also indicated that the presence of these genes decreased with depth but to a lesser extent when heavy vegetation was present. Genes for nitrification were much greater than denitrification genes in all sampling locations indicating more favorable conditions for the creation of nitrate and nitrite.

Another recent study conducted in Australia indicated that vegetation within biofilters, when paired with a saturated zone, leads to consistent effluent concentrations of all constituents year round through wet and dry periods (Glaister et al. 2014).

Nitrogen

Forms of nitrogen that are readily available for plant uptake include the inorganic forms of nitrate (NO_3^-) and ammonium (NH_4^+). Organic forms of nitrogen undergo microbial decomposition to these inorganic forms. In aerobic environments, ammonium is readily converted to nitrate via nitrification (Figure 2). In contrast, denitrification occurs when bacteria utilize nitrate as an electron acceptor to convert nitrate to nitrogen gas (N_2) thus removing it from the system. Since oxygen is a more efficient electron acceptor than nitrate, denitrification will occur at significant rates in an anoxic environment, decreasing total nitrogen (TN) concentrations. Nitrate is especially difficult to remove due to its high solubility. Soil has a net negative charge, so the negative charge of nitrate makes sorption unfavorable as opposed to the net positive charge of ammonium which is attracted to clay particles. This requires nitrate to be biologically transformed for removal.

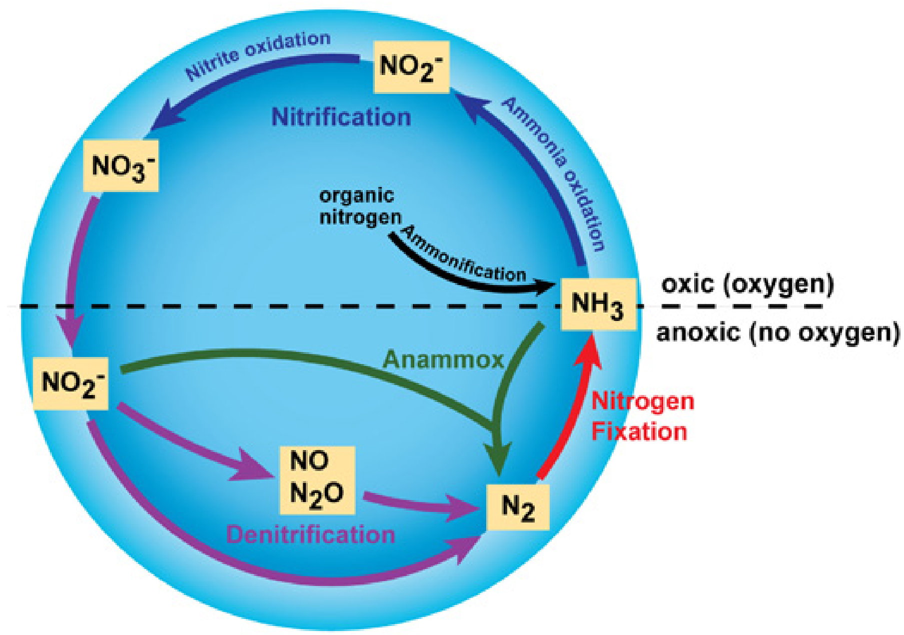

Figure 2: Transformations of nitrogen in oxic and anoxic environments (Bernhard 2010).

Sources of nitrogen in highway stormwater runoff include fertilizers, vegetation decay, and animal excrement (Burns 2012). Biofiltration studies vary greatly on the results of nitrogen removal. In a study focused on dissolved constituents, vegetated columns resulted in twice as much removal of TN (63-77%) as non-vegetated columns (Henderson et al. 2007). High NO_x removal (65%-93%) of vegetated columns was also observed with net zero or leaching observed in non-vegetated columns. Ammonia was removed in all configurations with and without vegetation (72-96%).

Hunt et al. (2006) found that nitrate removal can vary greatly at the field scale with 13% removal in a biofilter with sandy fill absent of organic matter and 75% removal in media with abundant organic matter. Based on soil core analysis, the finer soil gradation and organic matter in the second filter may have resulted in pocket saturated zones, facilitating denitrification. Total Kjeldahl Nitrogen (TKN) removal showed an opposite trend resulting in a net equivalent total nitrogen removal of approximately 40%. Addition of organic matter to planting soil has been encouraged to facilitate plant growth; however, organic matter in many cases also contributes to increased leaching of nitrogen compounds during decomposition (Hunt et al. 2012). Studies have also confirmed nitrate leaching from biofiltration experiments (Davis et al. 2006; Zinger et al. 2013). One study measured increasing concentrations of dissolved nitrogen with depth in the filter media (Hatt et al. 2006). Leaching may be due to the decomposition of organic matter and the oxidation of captured ammonia to nitrate.

Saturated Zone

Installation of a saturated zone in the lower layers of a biofilter has been studied as a means to create anoxic conditions for denitrification to occur. Another benefit to this improvement is lower velocity of water flowing through the filter due to a decrease in hydraulic head. This allows a longer contact time between the media and the pollutants in the stormwater. Similarly, retaining water in the bottom of the filter allows plants to utilize nutrients in this zone over time, potentially increasing removal (Glaister et al. 2014). Access to a constant source of water may also enhance the survival of plant plants during dry periods.

In an optimization study of 18 biofiltration columns planted with *Carex appressa*, varying depths of a saturated anoxic zone in the presence of a carbon source (wood chips) were tested (Zinger et al. 2007). With increasing saturated zone depth, ammonia and organic nitrogen removal slightly decreased while total nitrogen and NO_x removal increased. When the saturated anoxic zone was 450 mm in depth for a 900 mm height by 375 mm diameter column, >99% NO_x removal was achieved.

In a follow up study, Zinger et al. (2013) studied the effects of a submerged zone on the removal of nitrogen as well as phosphorus, total suspended solids (TSS), and heavy metals when an existing biofilter was retrofitted with a saturated anoxic zone. In this case, the microcosms were planted with two previously determined nitrogen inefficient species, *Dianella revolute* and *Microlaena stipoides*, and one highly efficient species, *Carex appressa* (Read et al. 2008). Before retrofitting with a saturated zone, ammonia removal was consistently above 90% in all columns. Results for NO_x agreed with previous studies (Davis et al. 2001; Read et al. 2008) in that leaching was observed. *Dianella* and *Microlaena* columns exhibited TN leaching while 45% to 65% removal from was observed with *Carex*. After the retrofitting, NO_x leaching was reduced, in some cases to net zero, in *Dianella* and *Microlaena* columns, and NO_x removal was enhanced in *Carex* columns. Ammonia removal was reduced in *Dianella* and *Microlaena* but unaffected in *Carex*. Dissolved organic nitrogen increased in all cases. Overall results indicated that vegetation choices that enhance nitrogen removal may be more effective than the presence of a saturated zone.

A North Carolina field study (Hunt et al. 2006) compared a constructed bioretention cell containing a saturated zone to a similarly constructed cell without a saturated zone. Results showed no statistically significant differences in the total nitrogen outflow. An increase in ammonium and slight decrease in nitrate was noted when the saturated zone was present. Ammonification occured at a faster rate under aerobic conditions than under anoxic conditions (Hunt et al. 2006).

In Barrett et al. (2013), filters constructed of masonry sand and loam sand media and planted with Big Muhly with a saturated zone showed slightly increased removal, but all configurations did not consistently increase nitrogen removal. This was a possible result of a submerged layer that was not thick enough to become anoxic consuming only the bottom 6 inches (one third) of the soil media.

Carbon Addition

As described above, a column study for an anoxic zone with a carbon source and a retrofitted column study without a carbon source showed that >99% nitrate removal was achieved with a carbon source (Zinger et al. 2007, 2013). Additionally, concentrations of 16S rDNA for nitrification and denitrification genes were present in high concentrations in areas containing high readily degradable material, suggesting that additional compost in a saturated layer may enhance denitrification (Chen et al. 2013).

In a comprehensive optimization study by Kim et al. (2003), afalfa, leaf mulch compost, newspaper, sawdust, wheat straw, and wood chips were compared as potential electron donors in a saturated zone. Sulfur-limestone and sulfur-only particles of varying size were also tested as inorganic substrates for chemolithotrophs. This study focused on microbial activity; no plants were involved. All columns performed better than the control column which was submerged without a carbon supplement. Alfafa and wheat straw both showed removal of greater than 95%; however, high TKN and turbidity was discharged. Results showed newspaper, wood chips, and small sulfur-limestone particles as the most effective electron donors. A flow study also displayed the resilience of bioretention systems; they continued to remove 90% nitrate after recovering from long drought periods (30 and 84 days). The provided explanation was that microbes switched to alternate metabolisms when stormwater was not entering the system and thus needed to recover once nitrogen species were reintroduced. As part of this study, pilot-scale bioretention boxes revealed complete removal of nitrate and nitrite species after remaining in the submerged zone for one week. A drawback of this method is that the carbon and nitrogen source will eventually need to be replaced as it degrades over time. Newspaper may exhibit the best longevity as the main constituent is lignin the ink prevents microbes from attacking the entire cellulose surface(Kim et al. 2003). A quick release and slow release carbon source may need to be combined such as a mixture of sawdust and hardwood mulch for optimum long-term treatment (Glaister et al. 2014).

Phosphorus

Sources of phosphorus in highway stormwater runoff include leaf decay from trees, fertilizers, and lubricants Studies have shown that total phosphorus can be greatly reduced within a biofilter because a majority of phosphorus is associated with particulate matter (Glaister et al. 2014; Hatt et al. 2007). In a study testing six different filter media types, total phosphorus was shown to have high removal in the upper portion of a soil-based filter; however, soluble phosphorus concentrations increased as a semi-synthetic stormwater flowed through the filter (Hatt et al. 2007). A follow up field study indicated that increased levels of phosphorus in the effluent may be due to high phosphorus content of the filter media (Clark and Pitt 2009; Hatt et al. 2009). This agrees with a field study in North Carolina in which phosphorus removal ranged from 65% to -240%, consistent with phosphorus concentration in the soil media (Hunt et al. 2006). Opposing studies have found that media depth showed no effect on total phosphorus or orthophosphate concentrations (Bratieres et al. 2008), or that greater removal of orthophosphate (70-80%) is found in the middle to bottom depths of pilot bioretention box filters (Davis et al. 2001). The latter study indicated that removal was likely due to favorable sorption to clay particles at a neutral pH. When TSS was not added to the synthetic stormwater mixture, 80% removal of total phosphorus was observed with 90-100% removal of orthophosphate (Henderson et al. 2007).

The effect of a saturated zone is unclear for phosphorus removal. Barrett et al. observed increased removal in the presence of a saturated zone (2013) while other studies indicate increased mobility of sorbed phosphorus from soil surfaces (Clark and Pitt 2009; Zinger et al. 2013).

In a study comparing biofiltration media, fly ash was found to have high potential for sorption of phosphorus when added as a supplement to the soil column. Fly ash was always mixed with soil since an entire column of fly ash can cause low hydraulic conductivity (Zhang et al. 2008).

Heavy Metals

In many biofiltration studies, indicator heavy metals have included copper, lead, and zinc. Common sources of copper include wear of bearings and brake linings, moving engine parts, fungicides, and insecticides (Burns 2012). Lead sources include automobile exhaust, wear of tires and bearings, and lubricating agents while zinc sources include oil, grease, and wear of tires (Burns 2012).

Results from multiple studies showed that metals removal was very high in biofiltration systems (Hatt et al. 2009; Hsieh and Davis 2005; Mitchell et al. 2011; Zinger et al. 2013). Removal was typically attributed to accumulation in soil and mulch due to their high organic matter content. Metal concentrations in the upper mulch layer were 2-3 times greater than measured in the soil media in a Massachusetts study (Davis et al. 2001). Studies also indicated that metals assimilation into plant material accounted for 5% or less of heavy metals removal (Davis et al. 2001; Dietz and Clausen 2006). Increased removal of heavy metals was observed in biofilters with a saturated zone in rain gardens (Dietz and Clausen 2006), while no effect was observed in column study (Zinger et al. 2013). Plants were observed to have very weak to no correlation with heavy metals removal (Read et al. 2010).

Suspended Solids

Sources of solids include wear of pavements and vehicles as well as atmospheric depositions (Burns 2012). Studies reviewed indicated a minimum of 76% TSS removal by biofiltration (Barrett et al. 2013; Bratieres et al. 2008; Hatt et al. 2009; Hsieh and Davis 2005; Mitchell et al. 2011).

Objectives

As described, studies have shown that the species of vegetation within a biofilter had an impact on the performance, specifically for nitrogen removal. Studies have observed varying success for total nitrogen removal with the installation of a saturated zone; more successful performance was observed when a carbon source was added within this layer. Phosphorus removal also varied based on the soil media and presence of a saturated zone. Heavy metals and suspended solids were typically removed at high extents in field and column studies.

Vegetation native to the southeastern United States has not been studied for biofiltration performance. The principal objective of this work was to identify the nutrient uptake efficiency of common Georgia native grasses as well as the inclusion of a saturated anoxic zone with an additional carbon source in typical Georgia topsoil biofiltration system.

CHAPTER 3

MATERIALS AND METHODS

Materials

The soil used to support plant growth consisted of gravel, sand, and mulch. Number 7 coarse aggregate was donated by the Vulcan Materials Company (Forest Park, Georgia). Number 10 sand was obtained from Sand-Rock Transit (Atlanta, Georgia). Both sand and gravel sources were pre-approved by GDOT (GDOT 2014) Topsoil and hardwood mulch were obtained from Green Brothers Earthworks (Marietta, Georgia). All materials were used as received. Three columns were tested with biomass fly ash incorporated into the soil substrate. The biomass ash used was formed from the combustion of forest, sawmill, and urban wood waste (Yeboah et al. 2014). The ash had a residual carbon content of 22.4%, loss on ignition (LOI) of 46.7%, and specific surface area of 116 m^2/g (Yeboah et al. 2014).

Biofiltration columns were constructed from polyvinyl chloride (PVC) with dimensions 813 millimeter height by 203 millimeter diameter (32 inch height by 8 inch diameter). Drainage outlets of 12.7 millimeters (½ inch) diameter were installed approximately 38 millimeters (1.5 inch) above the bottom of each column. Before packing, the columns were cleaned of all coolants and oils used during construction and rinsed in a hydrochloric acid solution. Columns were then thoroughly rinsed with tap water. Rubber test caps were added to the bottom of the columns and tightened. Gravel was added to the bottom of the columns to form a 6 inch layer thickness and hand tamped. Number 10 natural sand was then added to 16 of the columns to form a 10 inch layer thickness over the drainage gravel. In 16 additional columns, natural sand was hand mixed with 5% hardwood mulch by volume and added for a 10 inch layer thickness over the drainage gravel (as constructed Figure 3).

Three of the tested columns contained biomass fly ash. In one fly ash column, a natural sand layer was added to a 9 inch thickness with a 1 inch layer of biomass ash (Figure 3B). In the second column, a 9 inch layer of natural sand with 5% biomass ash by volume was added, with a 1 in layer of biomass ash. The third column contained a 10 inch layer of the sand/biomass mixture (Figure 3A), rather than mulch. All columns contain a 12 inch layer of silt loam topsoil (low-plasticity organic) with a hydraulic conductivity of 1.4E-4 cm/s and 8.3% organic matter, a two inch layer of hardwood mulch, and two inches of space for water ponding. A summary of all column configurations can be found in Table 2.

Chemicals used to prepare the synthetic stormwater (Table 3) included lead nitrate ($Pb(NO_3)_2$), cupric nitrate hemipentahydrate ($Cu(NO_3)_2 \bullet 2.5H_2O$), zinc nitrate hexahydrate ($Zn(NO_3)_2 \bullet 6H_2O$), sodium nitrate ($NaNO_3$), ammonium nitrate (NH_4NO_3), glycine ($C_2H_5NO_2$) and sodium phosphate diabasic anhydrous (Na_2HPO_4). Sodium metabisulfite ($Na_2S_2O_5$) was used for dechlorination of tap water. All chemicals were of certified grade from Fisher Scientific.

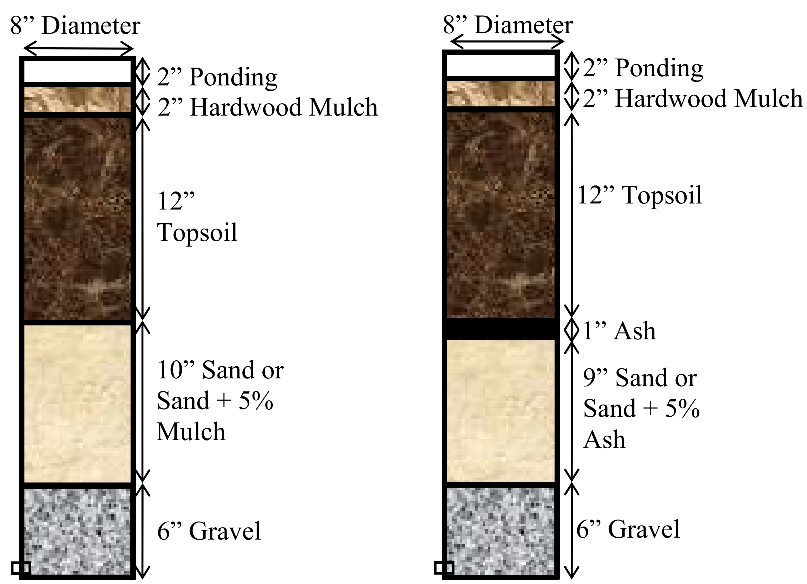

Figure 3A & B: Biofiltration column configurations. 32 columns of configuration A (left) configuration and 3 columns containing biomass ash (right) in configuration B.

An 8 foot by 12 foot Palram Snap & Grow greenhouse was constructed to protect the columns from precipitation (Figure 4). The greenhouse was located on the Georgia Tech campus in Atlanta, GA. The doors to the greenhouse remained open and two of the three back panels were removed to allow air to flow freely throughout the building. Columns were elevated in the greenhouse with cinderblocks to encourage drainage by gravity into sampling buckets. A 30% shade tarp was placed over the top of the greenhouse for temperature control. Additional photographs can be found in Appendix A.

Figure 4: View of the greenhouse on sampling day with all columns, blue sample buckets, batch mixing can, and shade tarp.

Grass Species

Native grass species were selected based on ability to withstand flood and drought conditions, sunlight needs, and availability. Species tested in this study included *Andropogon gerardii* (Big Bluestem), *Muhlenbergia capillaris* (Pink Muhly), *Chasmanthium latifolium* (River Oats), *Panicum virgatum* (Switchgrass), *Sorghastrum nutans* (Indiangrass), and *Carex cherokeensis* (Cherokee Sedge). *Cynodon dactylon* (Bermuda grass) was used as a control. All grasses except Indiangrass were obtained in quart containers from Niche Gardens (Chapel Hill, NC), while Indiangrass was donated in 4 in. plugs from Baker Environmental Nursery (Hoschton, GA). Three Indiangrass plugs were approximately equal in size to one quart container. Nursery soil was removed from root systems to extent possible before transplant to biofilter columns. All species were planted in four test columns. Two columns were designed with a saturated layer, and two columns were designed as free draining (traditional). Indiangrass was planted in columns containing biomass ash. Columns planted with Bermuda grass were cut down to approximately 1.5 inch height approximately once per month to avoid decomposition of grass in the column and replicate mowing in field conditions.

Table 2: Number of Replicates per Column Configuration

Plant Species	Saturated	Traditional	Saturated with 5% ash in sand	Traditional with 1" ash layer above sand
None	2	2	-	-
Bermuda Grass	2	2	-	-
Big Bluestem	2	2	-	-
River Oats	2	2	-	-
Cherokee Sedge	2	2	-	-
Pink Muhly	2	2	-	-
Switchgrass	2	2	-	-
Indiangrass	2	2	2	1

Methods

Synthetic Stormwater

Synthetic stormwater was used to provide comparable, consistent control of the inflow constituents and to reduce experimental artifacts. The concentration of contaminants (Table 3) was formulated with reference to a previous characterization study of highway stormwater runoff in Georgia (Burns 2012), as well as the average concentrations from the Federal Highway Administration's (FHWA) characterization study of North Carolina, Florida, and Tennessee highway runoff (Driscoll et al. 1990). Suspended solids were not added in this study due to the variable concentration of contaminants that has been observed with this practice. Instead, dissolved constituents were the main concern, since it is well established that TSS are removed at extents >88% in biofiltration columns (Barrett et al. 2013; Bratieres et al. 2008; Davis et al. 2001). The removal of TSS will have impact on associated contaminants; consequently, dissolved constituents were the focus in this study.

Table 3: Synthetic Stormwater Formulas

Pollutant	**Field Measured (Burns 2012)**	**FHWA Study (Driscoll 1990)**	**Average Synthetic Stormwater**	**Metals Spike (9/1/14)**	**Nutrient Spike (9/22/14)**	**Source Chemical**
Total Phosphorus (mg P/L)	0.08-1.29	0.65	0.74 ± 0.17	0.74	3.60	Na_2HPO_4
Total Nitrogen (mg N/L)	1.20-3.40	-	3.19 ± 0.42	4.66 ± 0.59	15.90 ± 0.15	-
Nitrate (mg N/L)	0.65-1.20	0.61	1.52 ± 0.28	2.27 ± 0.05	3.80	$NaNO_3$
Ammonium (mg N/L)	-	-	0.65 ± 0.18	1.03	3.33	NH_4NO_3
Organic Nitrogen (mg N/L)	-	1.60	1.01	1.36	8.77	$C_2H_5NO_2$
Copper (mg/L)	0.03	0.05	0.11 ± 0.03	0.33	0.16	$Cu(NO_3)_2$
Lead (mg/L)	0.01	0.34	0.25 ± 0.07	0.73	0.35	$Pb(NO_3)_2$
Zinc (mg/L)	0.12	0.20	0.44 ± 0.13	1.58	0.71	$Zn(NO_3)_2$

Tap water was added to a polyethylene batch can (Figure 4) container and mixed with a 1725 rotations per minute (rpm), 1/3 horsepower (hp) mixer motor, and 48 inch dual propeller shaft for approximately five minutes. Free chlorine was then measured using free chlorine micro check test strips (HF Scientific). Sodium metabisulfite ($Na_2S_2O_5$) was added for dechlorination at a ratio of 1.34 parts $Na_2S_2O_5$ per 1.0 part residual chlorine and mixed for a minimum contact time of five minutes (US EPA 2000). Chlorine concentrations were then measured to assure dechlorination was achieved before adding contaminants. Contaminants were mixed with the dechlorinated tap water for approximately fifteen minutes.

Synthetic stormwater was pumped from the tank through submersible pumps and delivered to the plants through a ¼ inch PVC irrigation system at a rate of approximately 0.4 L/min. Each column received approximately 11 liters with each watering event (AMEC Earth and Environmental et al. 2001). Watering was typically completed in two doses with an hour in between to avoid overfilling, particularly in ash columns which had an observed lower hydraulic conductivity. Stormwater was sampled as it came out of the irrigation system. Samples were collected in 3.5 gallons buckets after complete drainage. Buckets were mixed thoroughly and a 1 liter sample was transported to the lab in polyethylene bottles for analysis.

Sampling Schedule

All grasses were planted by April 17, 2014. Plants were watered with approximately 2.9 gallons of tap water twice weekly. A 30% shade tarp was installed to reduce temperatures inside the greenhouse to ambient outdoor temperatures. The first synthetic stormwater dosing was on June 6, 2014, with continued dosing twice a week (typically on Mondays and Thursdays). A whitefly infestation was identified on June 19, 2014. Leaves were hosed down with tap water to wash whiteflies loose of leaves and stems. An insecticidal soap was sprayed lightly on leaves to remove any surviving flies. The saturated layer condition was imposed on June 30, 2014. After a final pressure rinse on July 2, 2014 whiteflies seemed to be eliminated with continued monitoring thereafter through yellow sticky traps. Treated sampling was conducted on a regular schedule throughout the summer months (Table 4).

Table 4: Sampling Schedule

Test Condition	Number of Samples	Sample Dates
Average Stormwater	4	7/7/14, 7/21/14, 8/4/14, 8/18/14
Metals Spike	1	9/1/2014
Nutrient Spike	1	9/22/2014
Average after 2 week drought	1	10/6/2014

Watering with stormwater spiked with heavy metals was performed on September 1, 2014. Watering with stormwater spiked with nutrients was performed on September 22, 2014. Watering ceased after the September 22, 2014 watering event to impose drought conditions. Saturated layers were depleted due to plant uptake and evaporation by the end of the drought period. On October 6, 2014, a final sample was collected after a dosing with an average synthetic stormwater mixture.

Plant height was measured at the end of the study for all columns. A column of each configuration was also cut open to measure the depths and observe the density of root growth within the column. Soil was shaken loose of root systems to determine maximum root depth within the soil column. All grasses except Bermuda grass were planted at an operational underground sand filter in Canton, Georgia to compare survival in the greenhouse to survival in an outdoor biofiltration setting.

Sample Analysis

Collected samples were immediately tested for pH (XL60, Accumet) and turbidity (TB-200, Orbelco). They were then filtered through 0.45 μm Millipore nylon syringe filters. Samples were analyzed for nitrate, nitrite, phosphate, and ammonium via ion chromatography (ICS-1100, Dionex). An AS22 column and AERS 500 suppressor were utilized for anions with a 4.5mM sodium carbonate: 1.4mM sodium bicarbonate eluent. A CS16 with an ERS 500 suppressor and 36 mM methanesulfonic acid eluent was used for ammonium analysis. Samples were digested via *Standard Methods* 4500-P J, Persulfate method (APHA et al. 2012) to convert all nitrogen and phosphorus forms to nitrate and orthophosphate, respectively. Digested samples were measured through ion chromatography for total nitrogen while total phosphorus was measured through spectrophotometry (UV-1800, Shimadzu) at 880 nm via *Standard Methods* 4500-P E (APHA et al. 2012). Samples were prepared with 5% nitric acid and 1 ppm yttrium for analysis of copper, lead, and zinc through inductively coupled plasma optical emission spectroscopy (Optima 8000, Perkin Elmer).

All columns were averaged between two replicates except the traditional Indiangrass plus biomass ash column which did not have a replicate. For nitrogen, effluent concentrations are shown as mg N/L by form (nitrate + nitrite, ammonium, or organic) to indicate total nitrogen make up. Results for the first four collection dates in which columns were consistently dosed with an average synthetic stormwater are averaged and presented in the results section. For the synthetic stormwater spiked with metals, synthetic stormwater spiked with nutrients, and average stormwater after a two week drought, replicate columns were averaged for the single sampling event. Turbidity and pH data was collected for all sampling events except the first on July 7, 2014.

CHAPTER 4

RESULTS AND ANALYSIS

Outflow from the biofiltration columns was collected and analyzed for nitrogen, phosphorus, and metal removal extents. The following figures summarize removal results as a function of species and test conditions. Removal was calculated by subtracting the effluent concentration by the influent concentration and dividing by the influent concentration. Comprehensive data for all experiments can be found in Appendix B.

Nitrogen

Nitrogen results are displayed in terms of concentration to highlight the proportion of nitrate and nitrite, ammonia, and organic nitrogen in relation to total nitrogen.

During the first two months of stormwater monitoring, total nitrogen leaching was commonly observed. Removal was achieved in columns planted with Big Bluestem, Switchgrass, and Indiangrass in saturated columns. Significantly greater removal ($p < 0.0002$) was found in the saturated condition as compared to the traditional condition (Figure 5 and Figure 6).

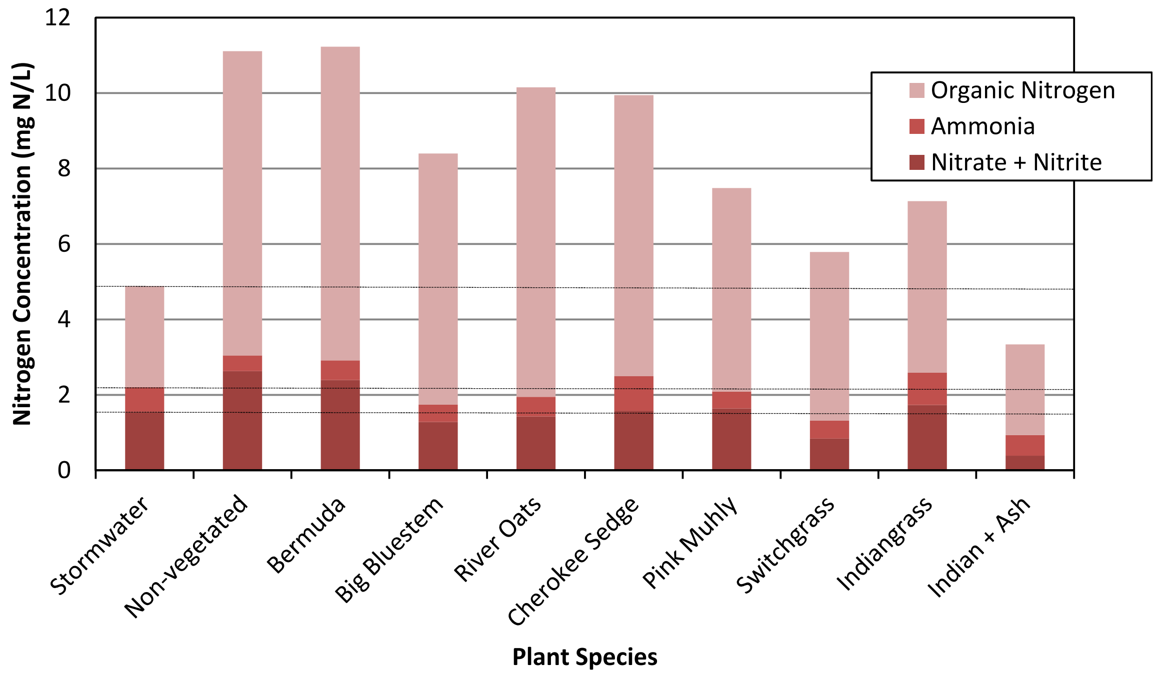

Figure 5: Nitrogen species concentration means by plant species with influent concentration dashed lines for traditional column effluent dosed with average synthetic stormwater.

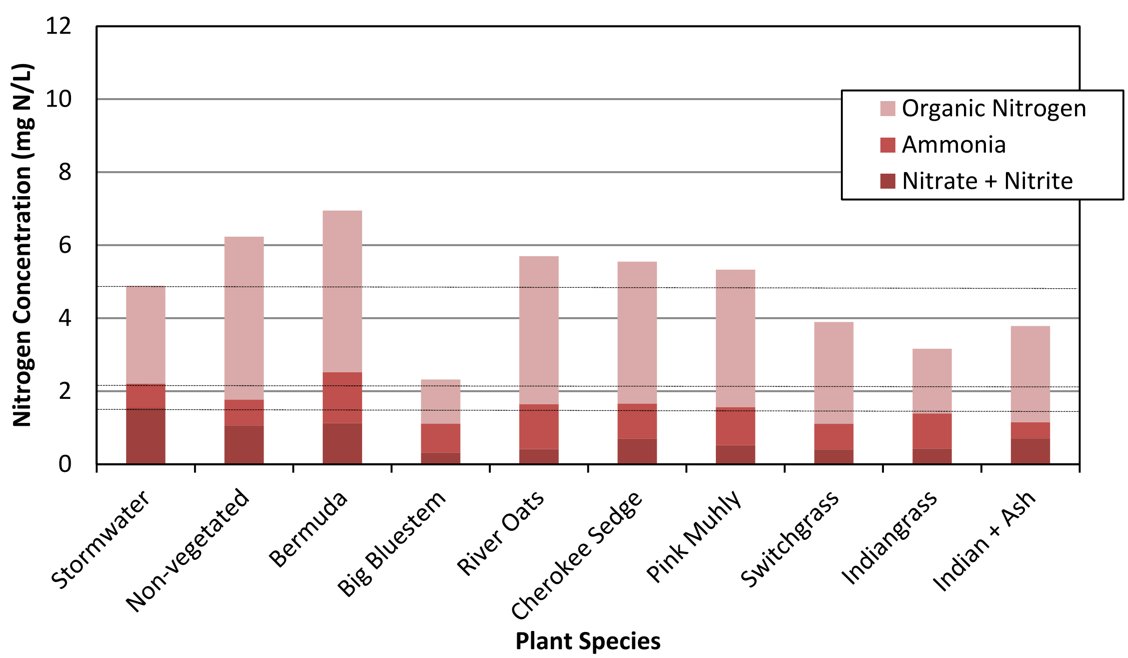

Figure 6: Nitrogen species concentration means in effluent by plant species with influent concentration dashed lines for saturated columns dosed with average synthetic stormwater.

In the traditional columns, total nitrogen leaching was common across all species ranging from 4% to 76% net export. In the saturated condition, total nitrogen ranged from 5% export to 70% removal in the case of Big Bluestem. The Indiangrass column with biomass ash lenses resulted in an average 32% removal of total nitrogen in the aerobic condition and 11% removal in the saturated condition. Ammonia concentrations typically decreased, while nitrate concentrations increased in the case of traditional columns, which was consistent with the nitrogen degradation processes occurring in aerobic conditions. The saturated layer increased denitrification as expected with nitrate removals ranging from -55% to 46% in the traditional configuration and 27% to 79% in the saturated configuration; however, increased concentrations of ammonia were observed. The presence of biomass ash seemed to be more effective in the reduction of nitrogen species in the traditional condition when compared to the saturated condition, with removal extents of 75% and 54% respectively. Organic nitrogen in the soil seemed to largely contribute to leaching. Big Bluestem, Switchgrass, and Indiangrass all showed positive removal extents in descending order.

When the stormwater inflow was spiked with heavy metals, an overall increase of nitrogen leaching was observed, especially in both the traditional and saturated configurations of columns planted with Bermuda grass (Figure 7 and Figure 8).

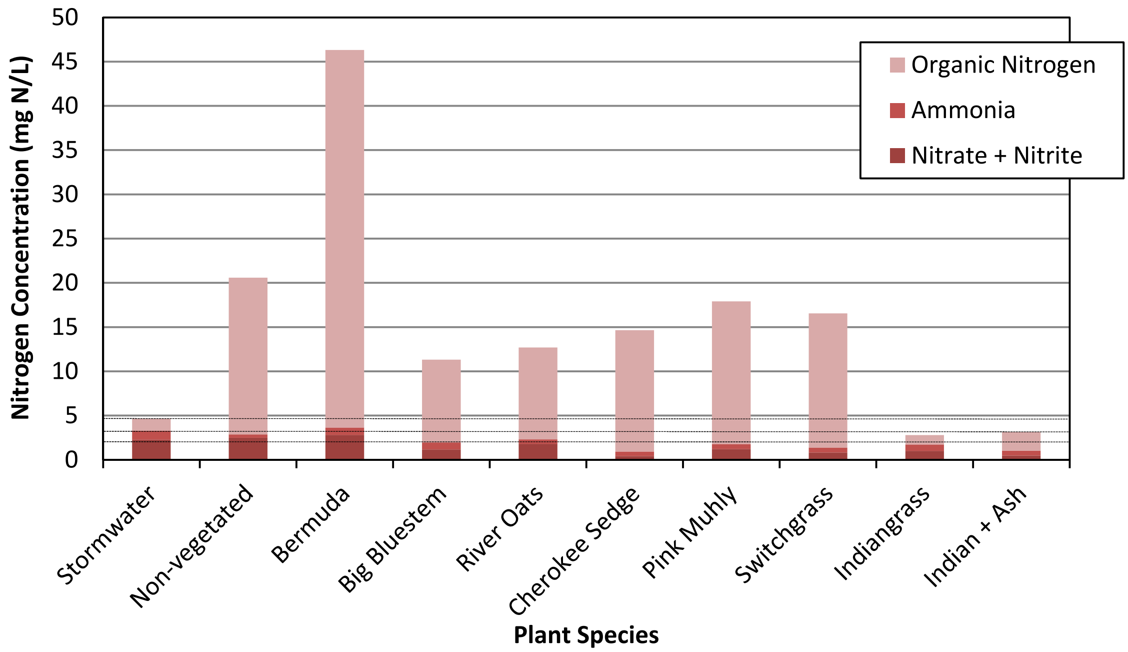

Figure 7: Nitrogen species concentration means in effluent by plant species with influent concentration dashed lines for traditional columns dosed with metals spiked stormwater.

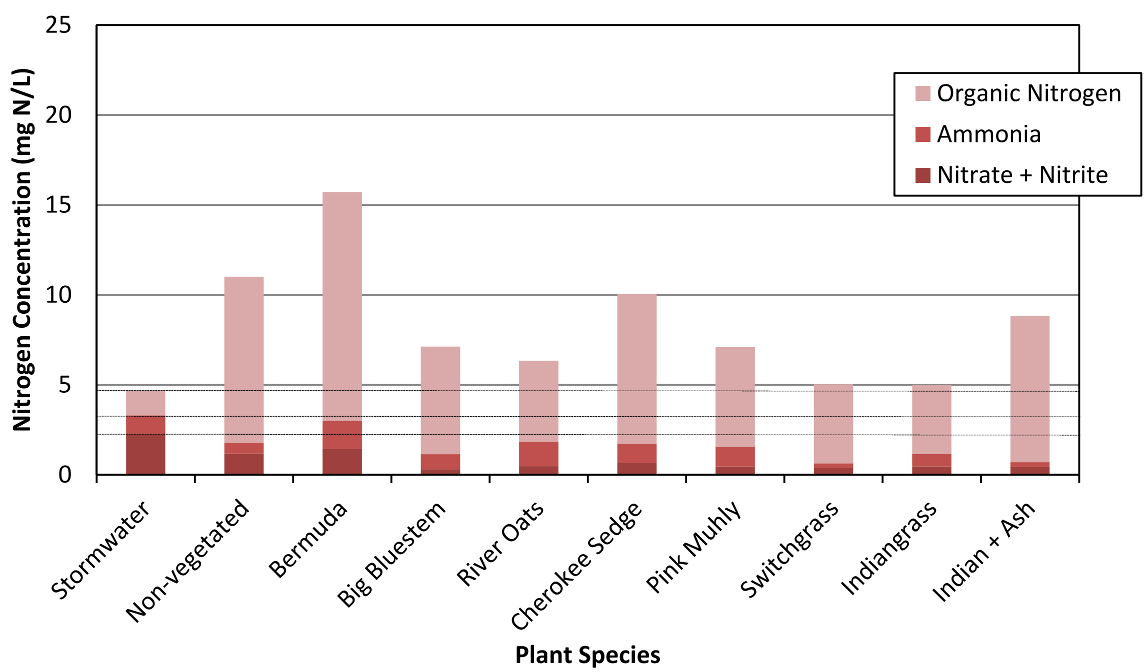

Figure 8: Nitrogen species concentration means in effluent by plant species with influent concentration dashed lines for saturated columns dosed with metals spiked stormwater.

The metal spiked synthetic stormwater contained a slight increase of nitrate (1.52 to 2.27 mg N/L) and total nitrogen (3.19 to 4.66 mg N/L) since metal chemicals were in the form of nitrate. Watering with this stormwater resulted in much larger amounts of total nitrogen leachate from the columns in both the saturated and traditional configurations. Saturated columns exported nitrogen at removal extents of -7% to -115% for native grasses, -237% for Bermuda grass, and -136% in the control. Traditional columns ranged from -283 to 53% for Pink Muhly and Indiangrass respectively. The leaching nitrogen is predominantly in the form of organic nitrogen since NO_x removal and NH_4 removal increased in all columns.

The third stormwater dosage type with spiked nutrient concentrations resulted in similar trends to that of the metal spiked stormwater, when compared to the average stormwater experiments (Figure 9 and Figure 10).

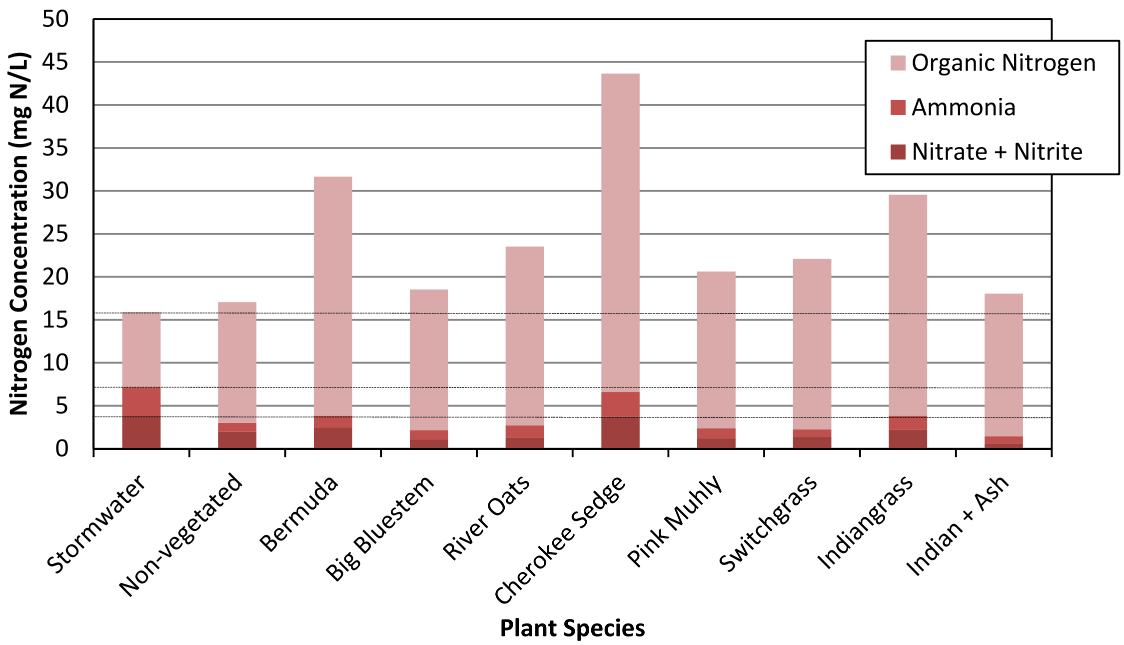

Figure 9: Nitrogen species concentration means in effluent by plant species with influent concentration dashed lines for traditional columns dosed with nutrient spiked stormwater.

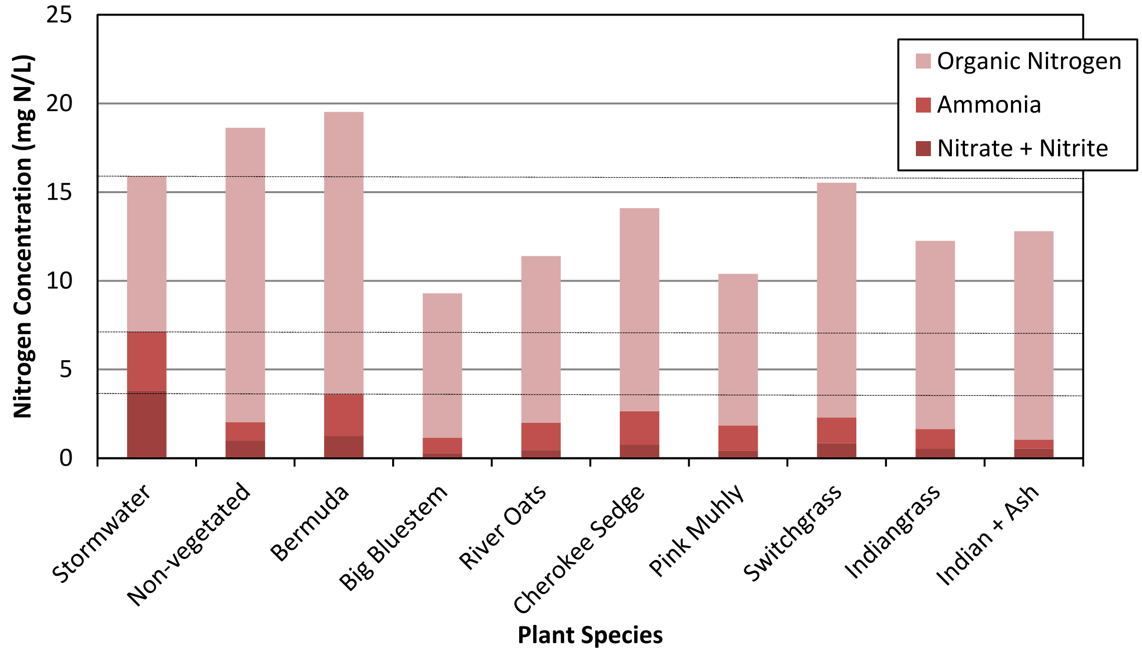

Figure 10: Nitrogen species concentration means in effluent by plant species with influent concentration dashed lines for saturated columns dosed with nutrient spiked stormwater.

All nitrogen concentrations were intended to be increased five times the average synthetic stormwater mixture; however, nitrate concentrations were measured to be approximately 2.5 times the average. With these increased concentrations, TN removal suffered slightly in most cases with overall removal in the traditional columns ranging from -174% with Cherokee Sedge and -17% with Big Bluestem. In the saturated condition, TN removal ranged from 2% to 42% with Switchgrass and Big Bluestem respectively. Removal of nitrate were greatly enhanced up to 72% and 92% with Big Bluestem in the traditional and saturated conditions, respectively. Similarly, percent removal for ammonium and Big Bluestem were 67% traditional and 74% saturated.

Lastly, results for the final experiment in which columns were dosed with an average stormwater mixture after two weeks of drought have mixed results as compared to the regular dosing of average stormwater (Figure 11 and Figure 12).

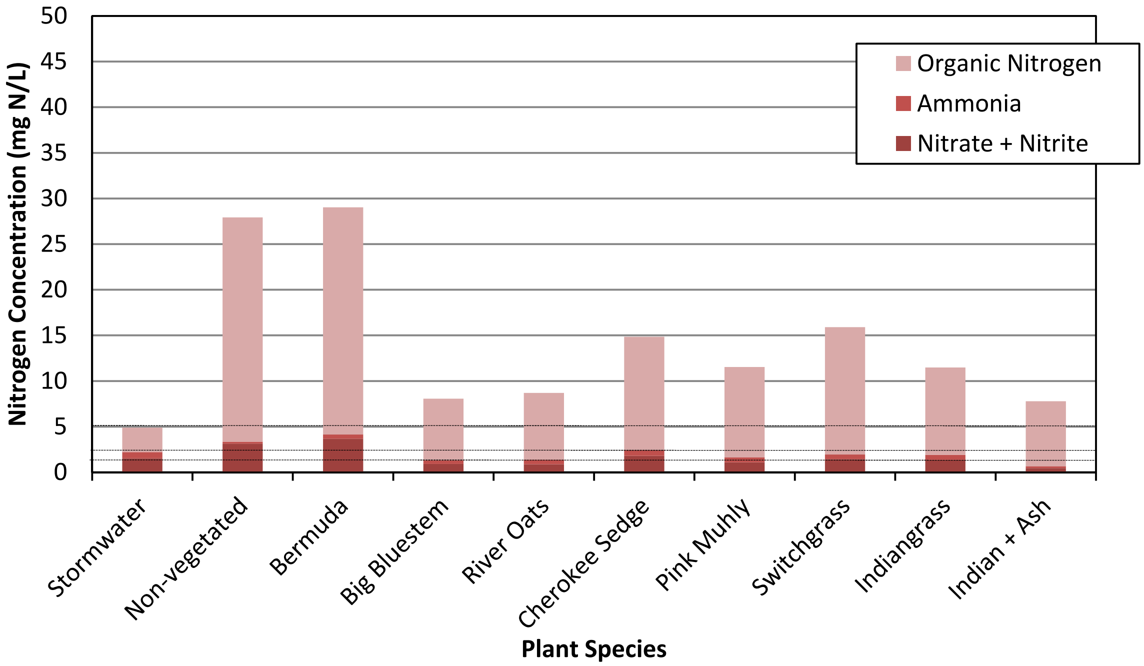

Figure 11: Nitrogen species concentration means in effluent by plant species with influent concentration dashed lines for traditional columns dosed with an average synthetic stormwater after two weeks of drought conditions.

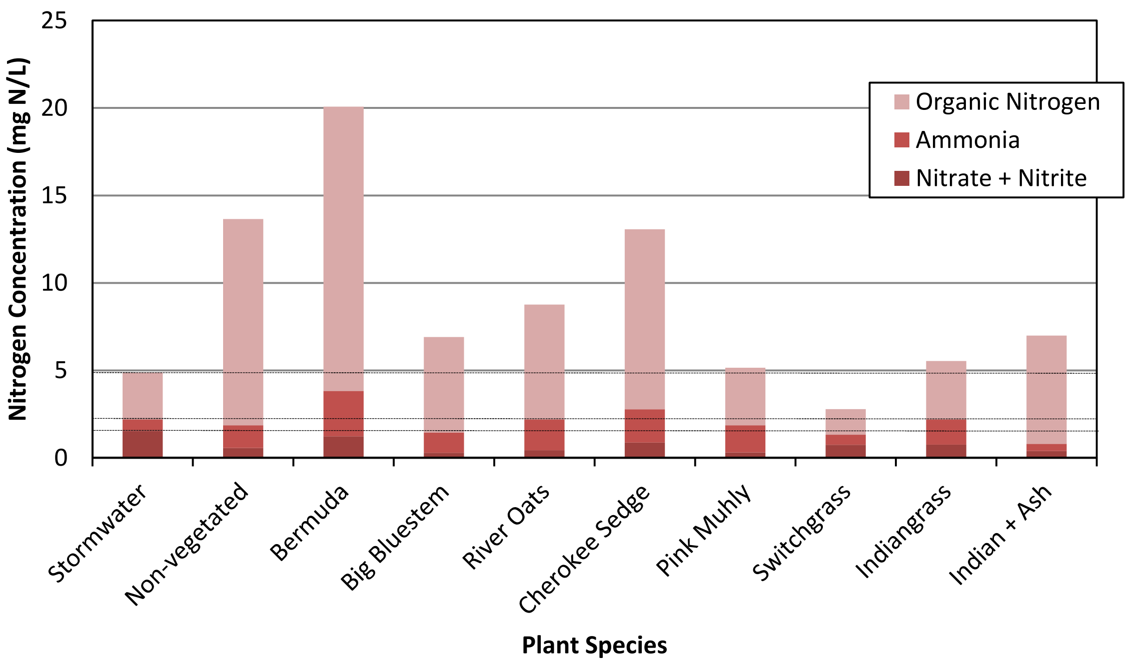

Figure 12: Nitrogen species concentration means in effluent by plant species with influent concentration dashed lines for saturated columns dosed with an average synthetic stormwater after two weeks of drought conditions.

To compare the trends of the different column configurations and stormwater doses, the traditional configuration was used as the baseline, and removal for different column configurations were subtracted from that of the traditional configuration with average stormwater (Figure 13 for total nitrogen, Figure 14 for nitrate + nitrite, and Figure 15 for ammonium). The traditional column configuration with metals spiked synthetic stormwater was the most common condition observed for high extents of total nitrogen leaching. Saturation tended to increase TN removal in almost all cases, except in the presence of biomass fly ash.

The carbon addition of mulch in the saturated layer will degrade over time altering the life of the biofilter. In the long term, decaying roots will become readily degradable carbon sources as plants turnover their root systems through the growing season.

Nitrate was removed at variable extents within vegetated columns ranging from -17% to 92% with the highest removal observed in the saturated, nutrient spiked experiment and lowest rate observed in traditional columns after a drought period. Across all experiments, nitrate removal ranged from 43% to 92% in saturated vegetated columns and -17% to 81% in traditional vegetated columns. Control columns with Bermuda grass or non-vegetated had nitrogen removals ranging from -139% (traditional) to 74% (saturated). The presence of biomass ash seemed to decrease the removal of nitrate in all experiments. High removal extents of ammonium were observed in the traditional columns with aerobic conditions as opposed to saturated columns. Highest removals of total nitrogen were typically observed from Big Bluestem, Switchgrass, and Indiangrass.

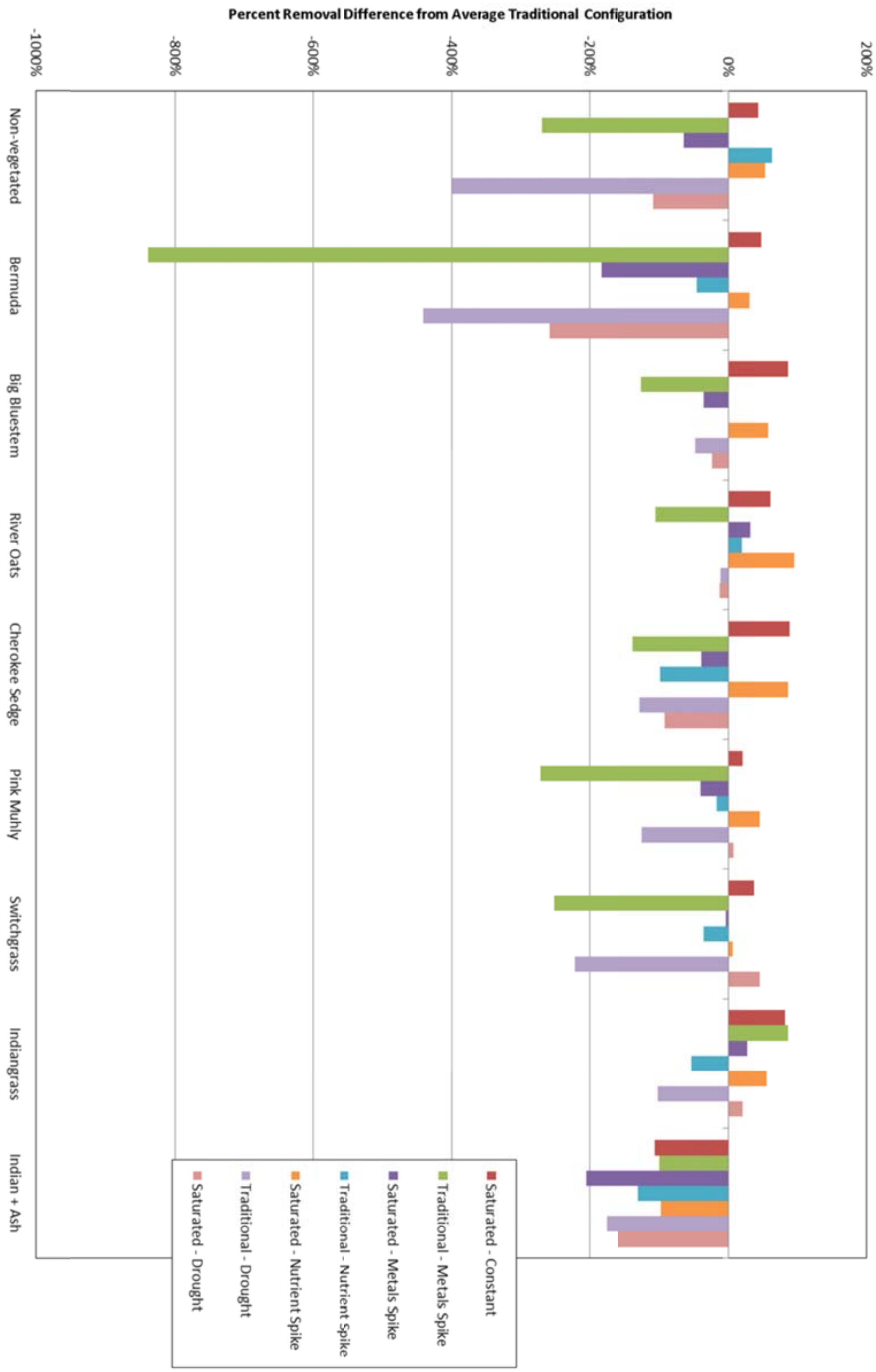

Figure 13: Difference of total nitrogen removal from the traditional configurations dosed with average stormwater.

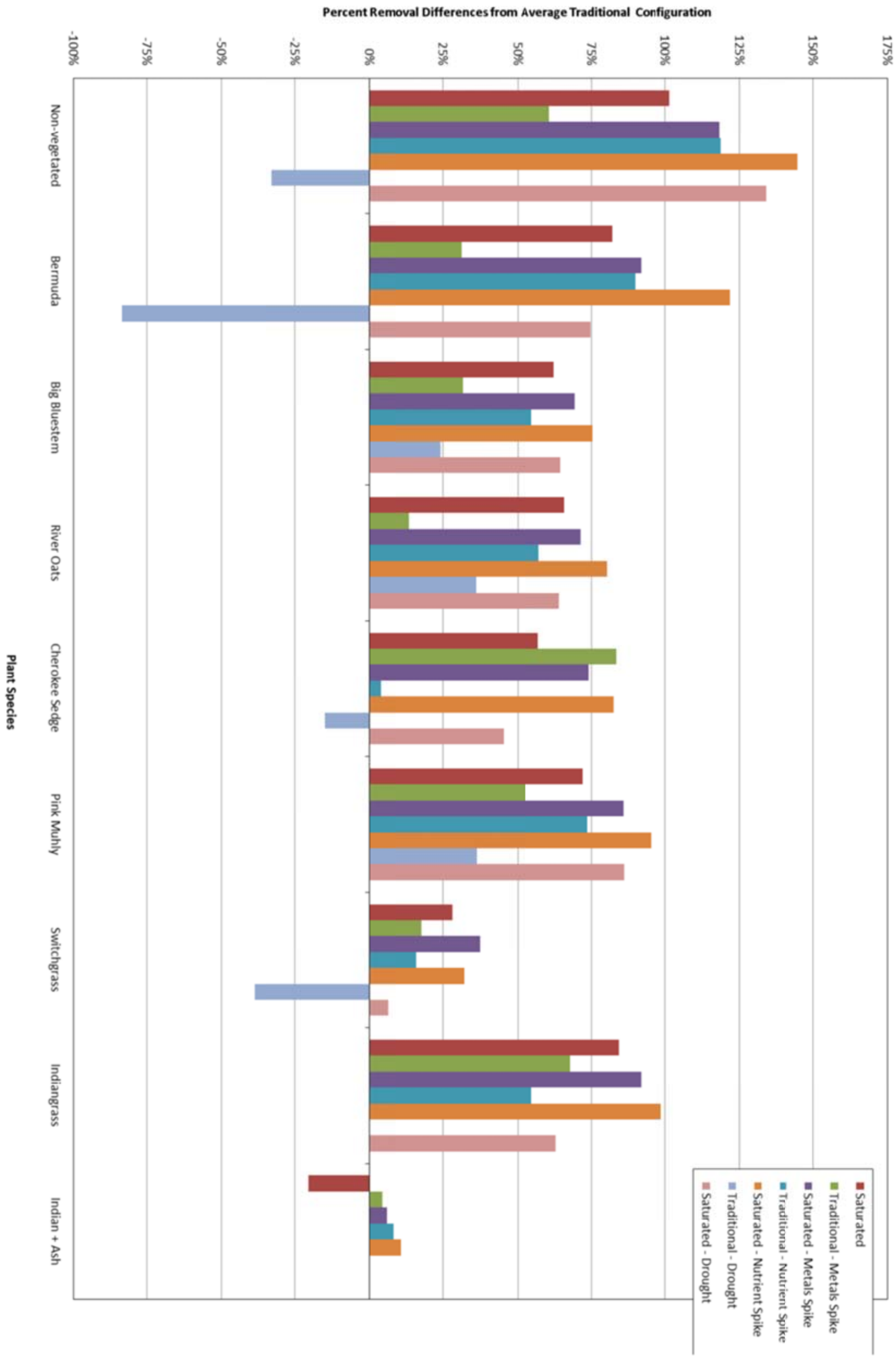

Figure 14: Difference of nitrate removal from the traditional configurations with average stormwater.

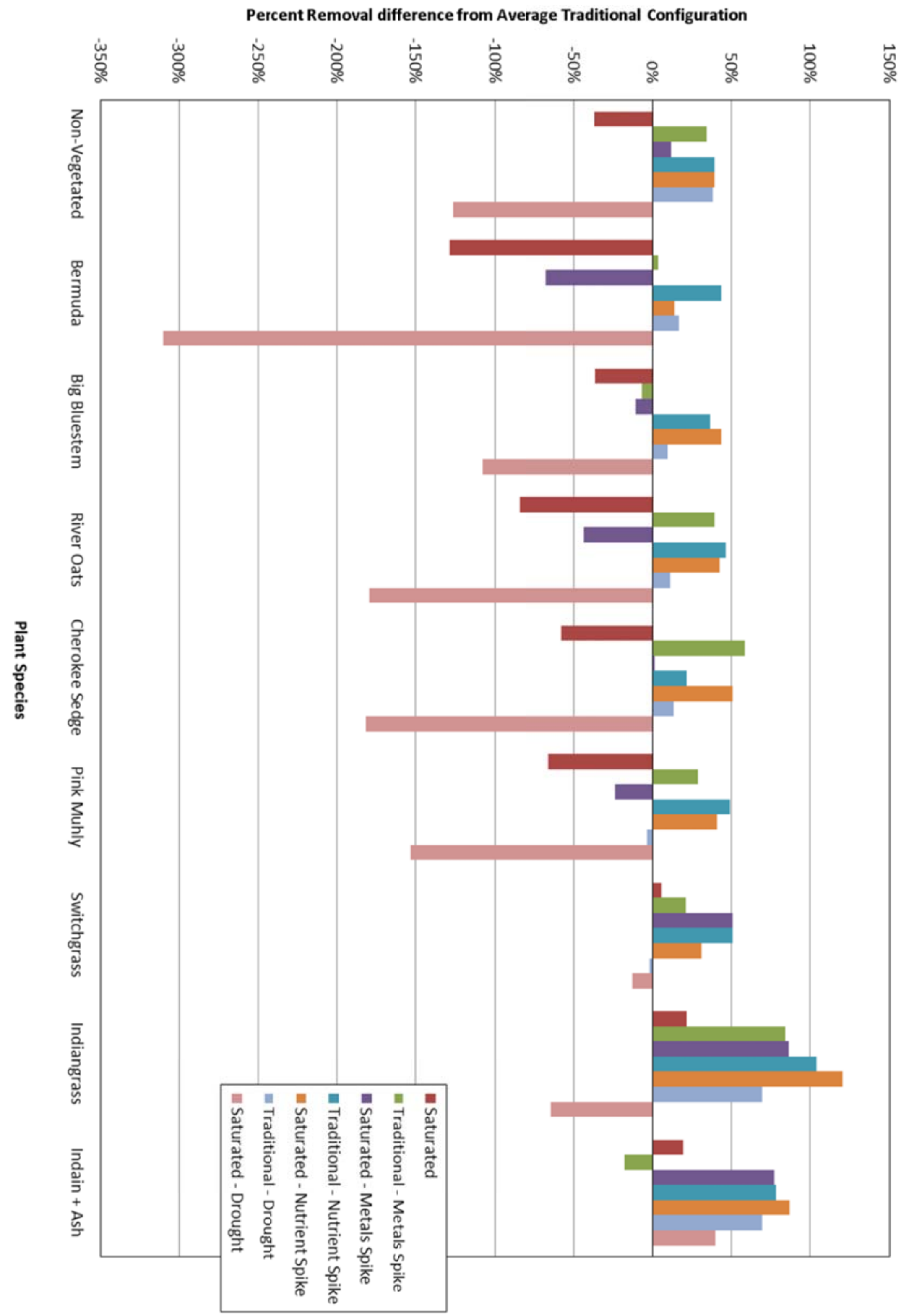

Figure 15: Difference of ammonia removal from the traditional configurations with average stormwater.

Phosphorus

Total phosphorus removal ranged from 50 to 90% in the saturated condition and 47 to 67% in the traditional, free-draining condition (Figure 16). Greater removal in the saturated condition ($p < 0.001$) supported the findings of Bratieres et al. (2008) but conflicted with those of Zinger et al. (2013). High removal in the traditional condition also agreed with previous work (Henderson et al. 2007). Columns including ash exhibited the lowest removal efficiency. In most experiments, the non-vegetated columns exhibited similar removal as compared to vegetated columns, indicating that sorption may be the primary mechanism for removal of phosphorus.

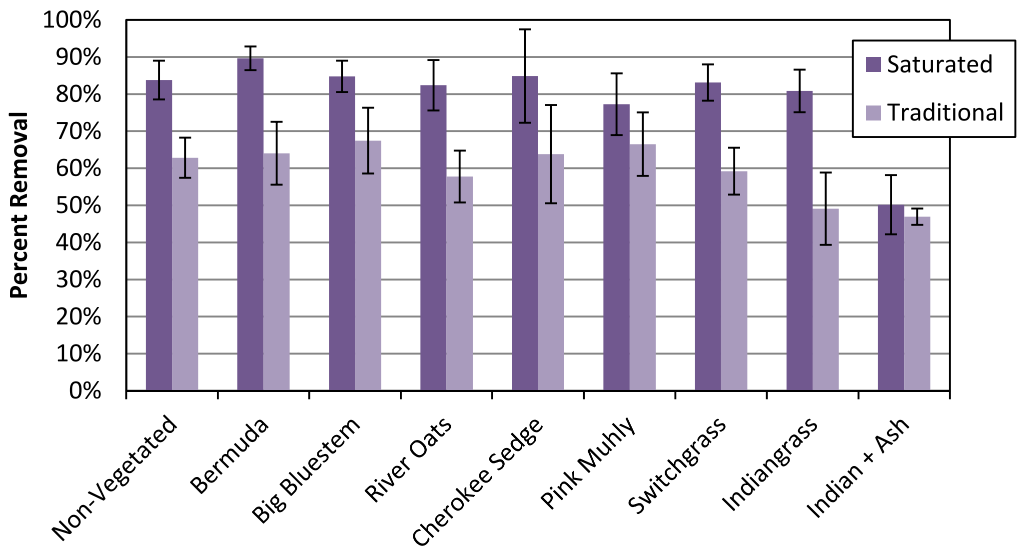

Figure 16: Total phosphorus removal by plant species for columns dosed with average synthetic stormwater.

Increased concentrations of heavy metals in stormwater runoff were accompanied by increased removal of total phosphorus in both the saturated and traditional configurations (Figure 17).

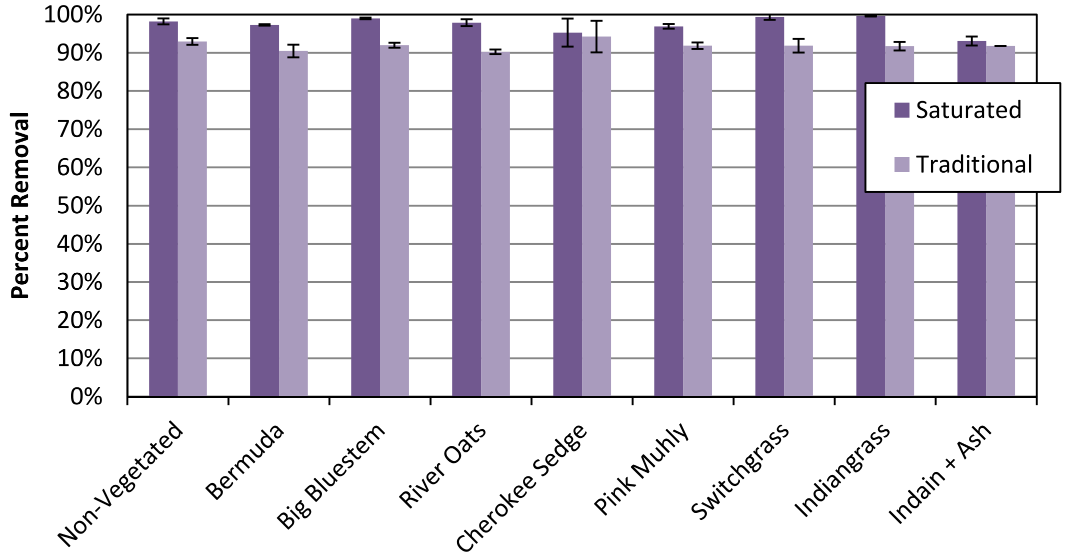

Figure 17: Total Phosphorus removal by plant species for columns dosed with metal spiked synthetic stormwater.

Higher removal in the presence of heavy metals likely indicated precipitation reactions. These precipitation reactions are commonly used to immobilize heavy metals, specifically lead, in contaminated soils (Fang et al. 2012). When phosphorus concentrations were increased to approximately five times "average" concentrations, removal varied greatly (Figure 18).

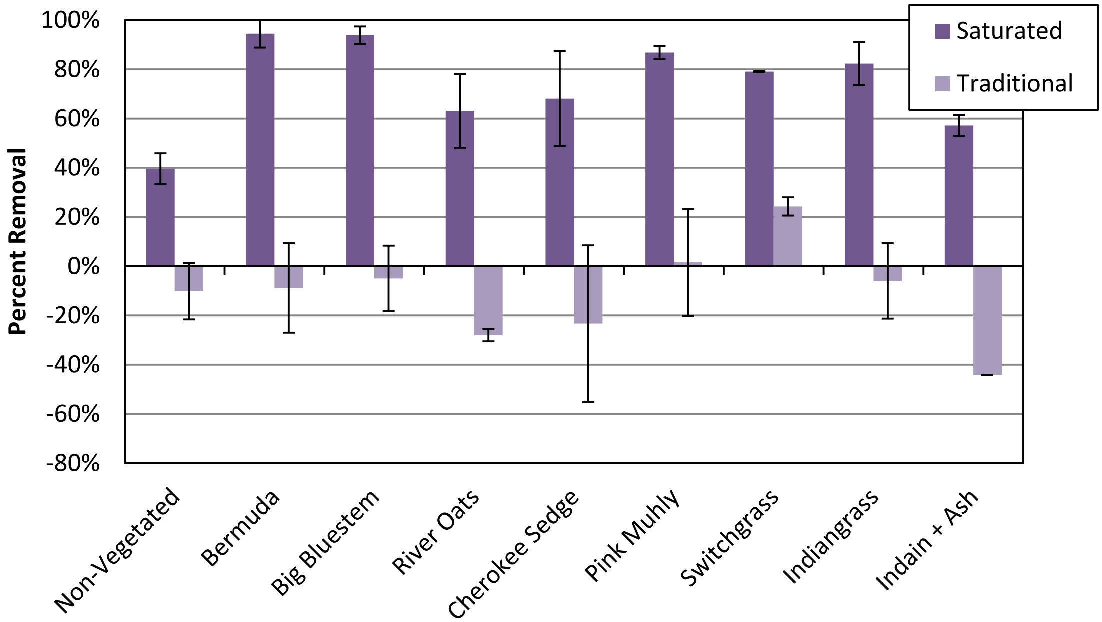

Figure 18: Total phosphorus removal by plant species for columns dosed with nutrient spiked synthetic stormwater.

This may indicate a greater impact of plant uptake than in the average condition as the removal extent for the non-vegetated column in the saturated condition was significantly lower (40%) when compared to the grass species (57% to 94%). In this case, traditional columns typically noted an export of phosphorus for all species except Pink Muhly and Switchgrass. Ash columns exhibited high amounts of export (-44% removal) in the traditional condition. After the two week drought period, the saturated columns demonstrated higher removal than the traditional columns (Figure 19).

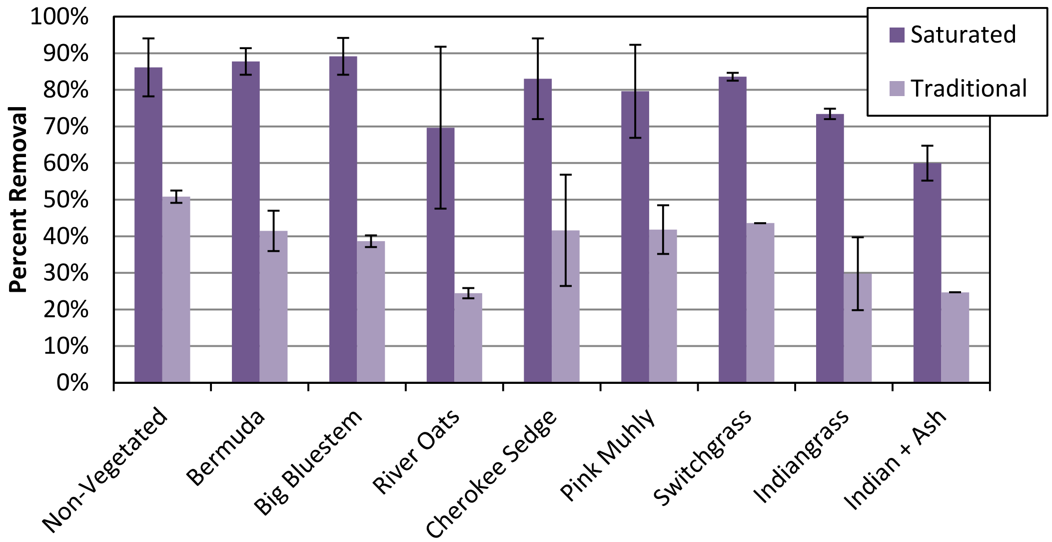

Figure 19: Total phosphorus removal by plant species for columns dosed with average synthetic stormwater after two weeks of drought conditions.

Saturated columns maintained an average of 80 to 90% removal during average conditions; however, traditional column removal dropped from around 60% to around 40% on average. Ash columns resulted in the least removal in both traditional and saturated conditions after the drought period.

When comparing all removals to that of the traditional configuration under average conditions (Figure 20), the results demonstrated that the two conditions of traditional configuration under high nutrient conditions and the traditional configuration after drought conditions showed greatly reduced performance. In contrast, a configuration with a permanent saturated layer enhanced performance. An increased concentration of heavy metals demonstrated the greatest enhancement to phosphorus removal; it is believed this was due to precipitation reactions within the filter media, but is a removal mechanism that will be explored in more detail in future studies.

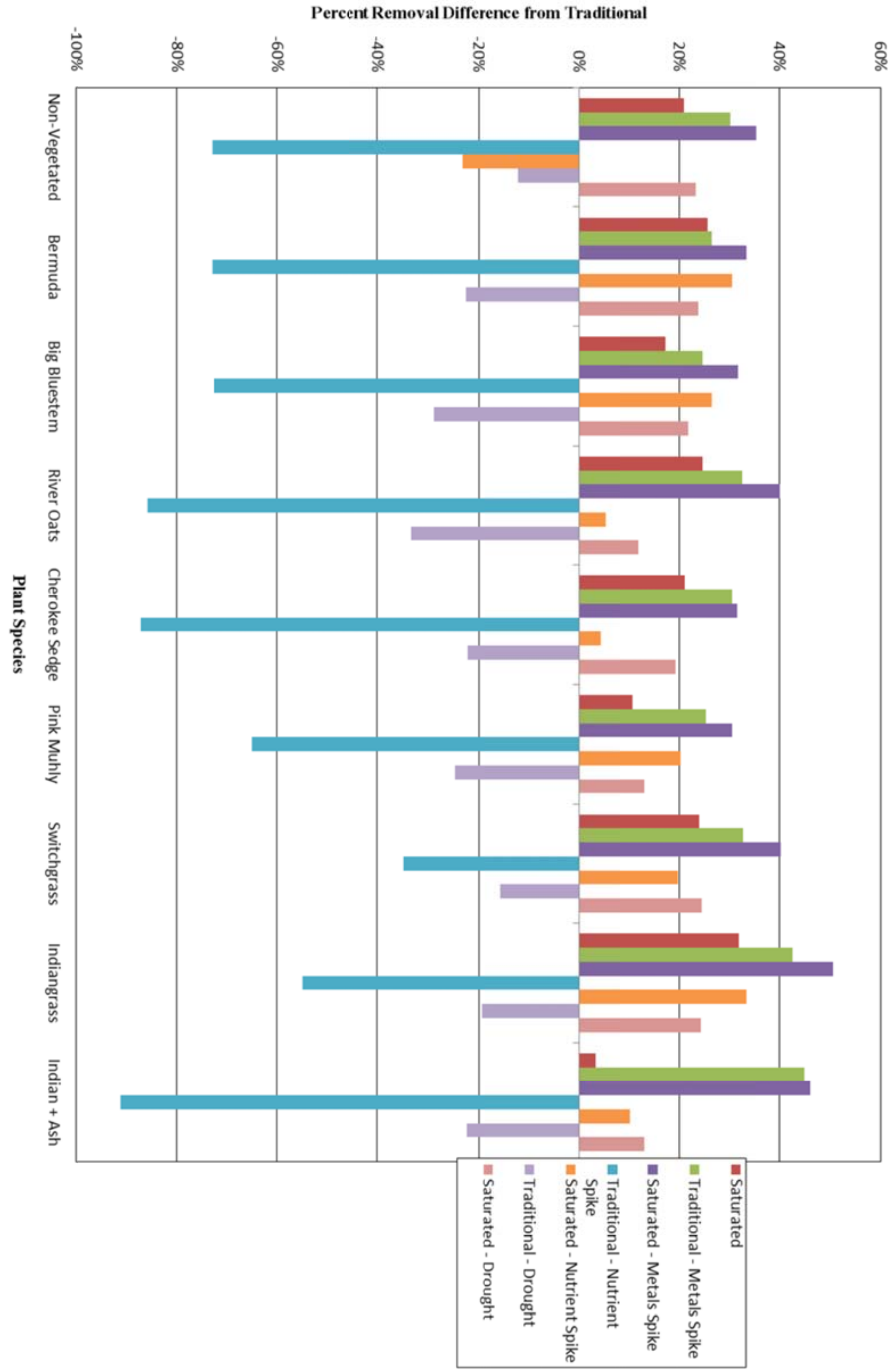

Figure 20: Total phosphorus removal differences from traditional configuration with average synthetic stormwater.

Heavy Metals

Copper

For all column configurations and all synthetic stormwater formulas, copper was removed at extents greater than or equal to 82%. Removal in the traditional monitored conditions were greater than 92% with the saturated condition resulting in removals greater than 99% (Figure 21).

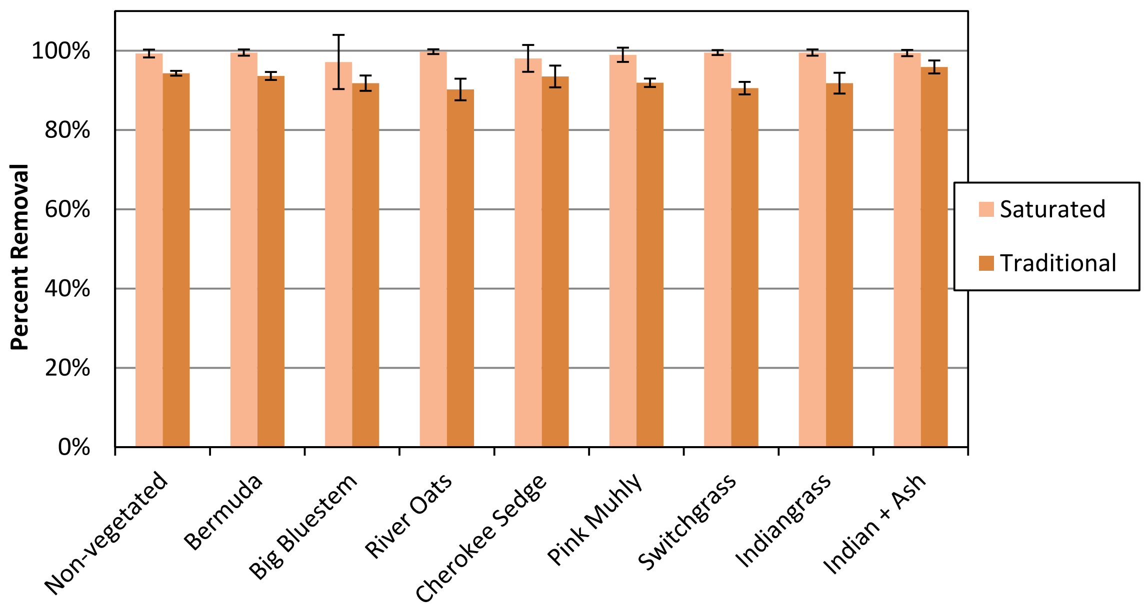

Figure 21: Copper removal by plant species for columns dosed with average synthetic stormwater.

The increase in removal observed in the saturated columns was statistically significant ($p < 0.001$).

Spiked metals concentrations in stormwater resulted in increased metals removal (Figure 22).

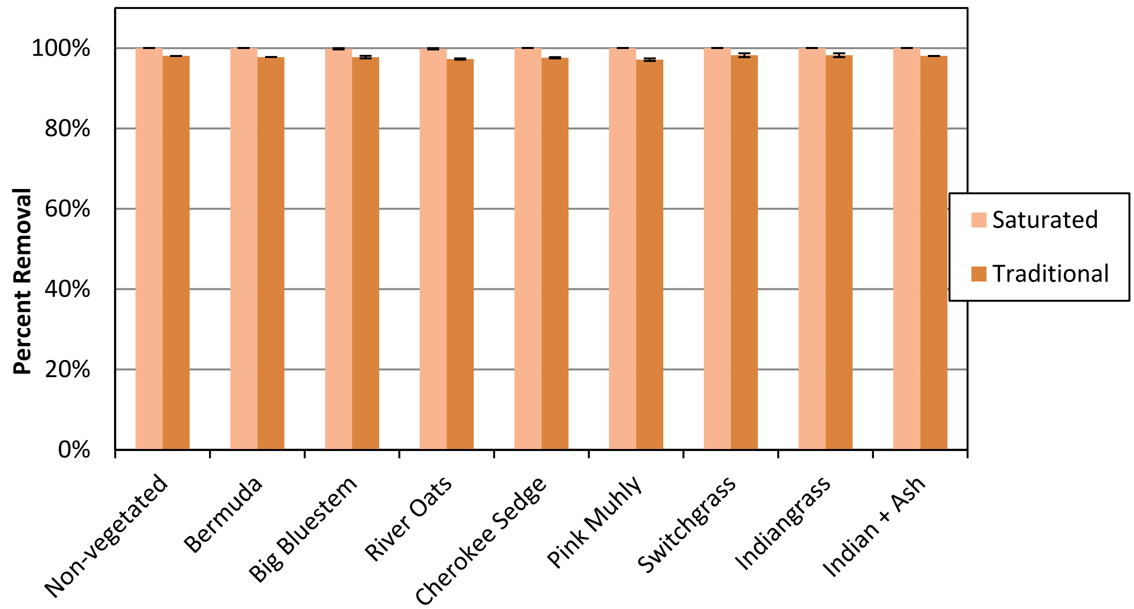

Figure 22: Copper removal by plant species for columns dosed with metal spiked synthetic stormwater.

Increased nutrient concentrations in the influent resulted in the lowest removal extents of copper in the traditional configuration but still larger than 82% in all cases (Figure 23).

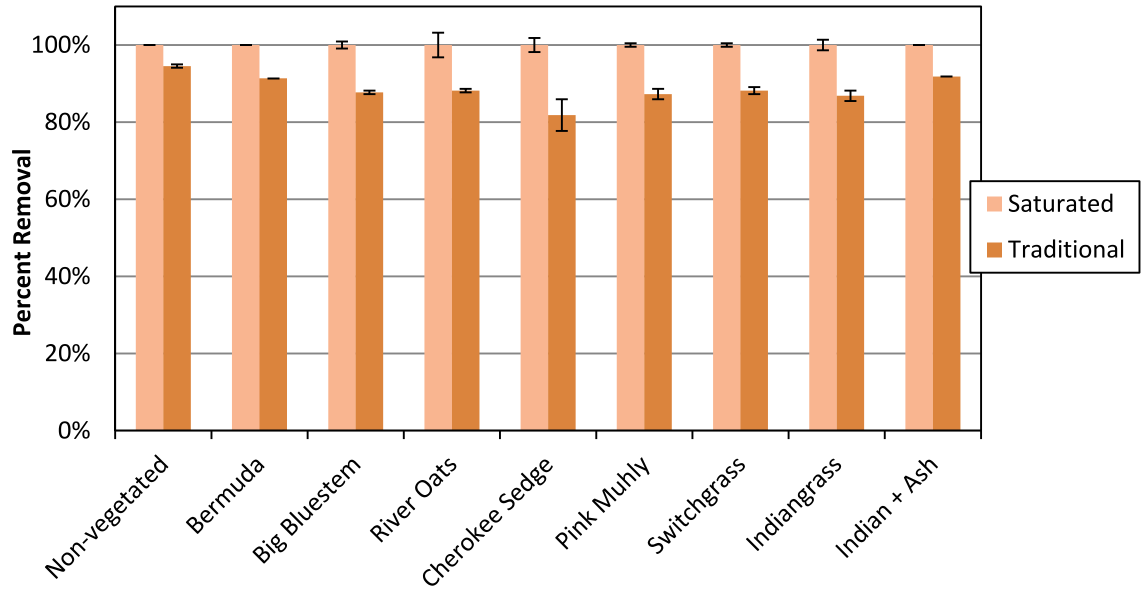

Figure 23: Copper removal by plant species for columns dosed with nutrient spiked synthetic stormwater.

After two weeks of drought, copper removal was consistent with that of the average stormwater conditions (Figure 24).

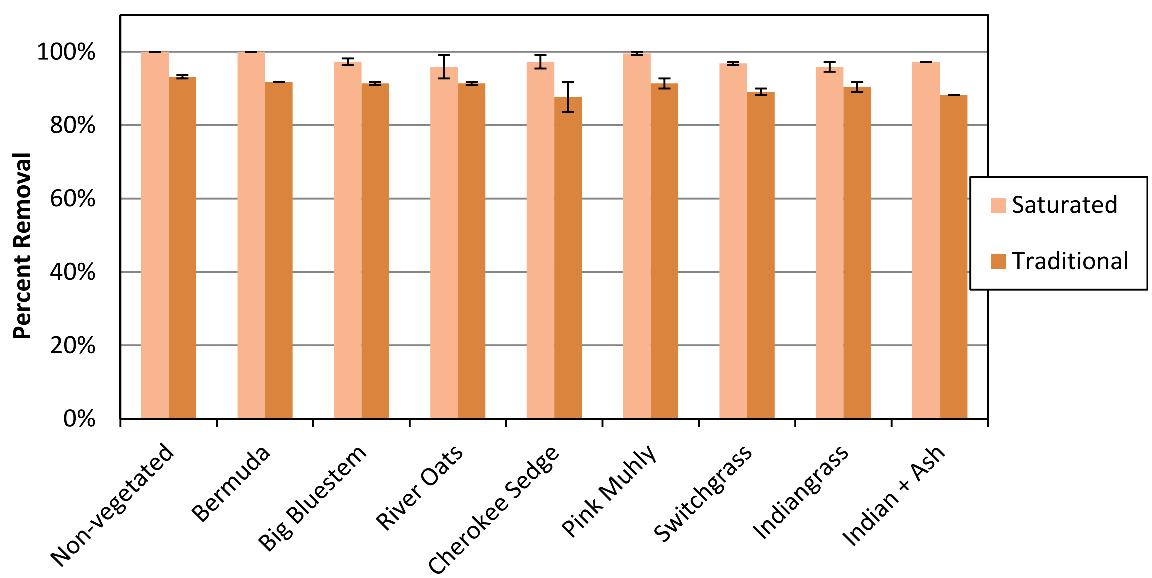

Figure 24: Copper removal by plant species for columns dosed with average synthetic stormwater after two weeks of drought conditions.

Through all experiments, variation in the uptake of copper among different plants species in comparison to non-vegetated columns was not observed ($p > 0.05$). This is consistent with previous findings, which demonstrated that plant uptake accounted for 5% or less for metal removal in a biofiltration setting (Davis et al. 2014; Dietz and Clausen 2006). In comparing copper removal by column configuration, saturation of the column resulted in statistically significant increase of performance ($p < 0.001$) (Figure 25). Highest removal extents were observed when metals concentrations were increased in the saturated configuration, while lowest removals occurred in traditional columns with high nutrient concentrations. Variation in copper removal was typically within 10% of removals in the traditional column configuration with average stormwater.

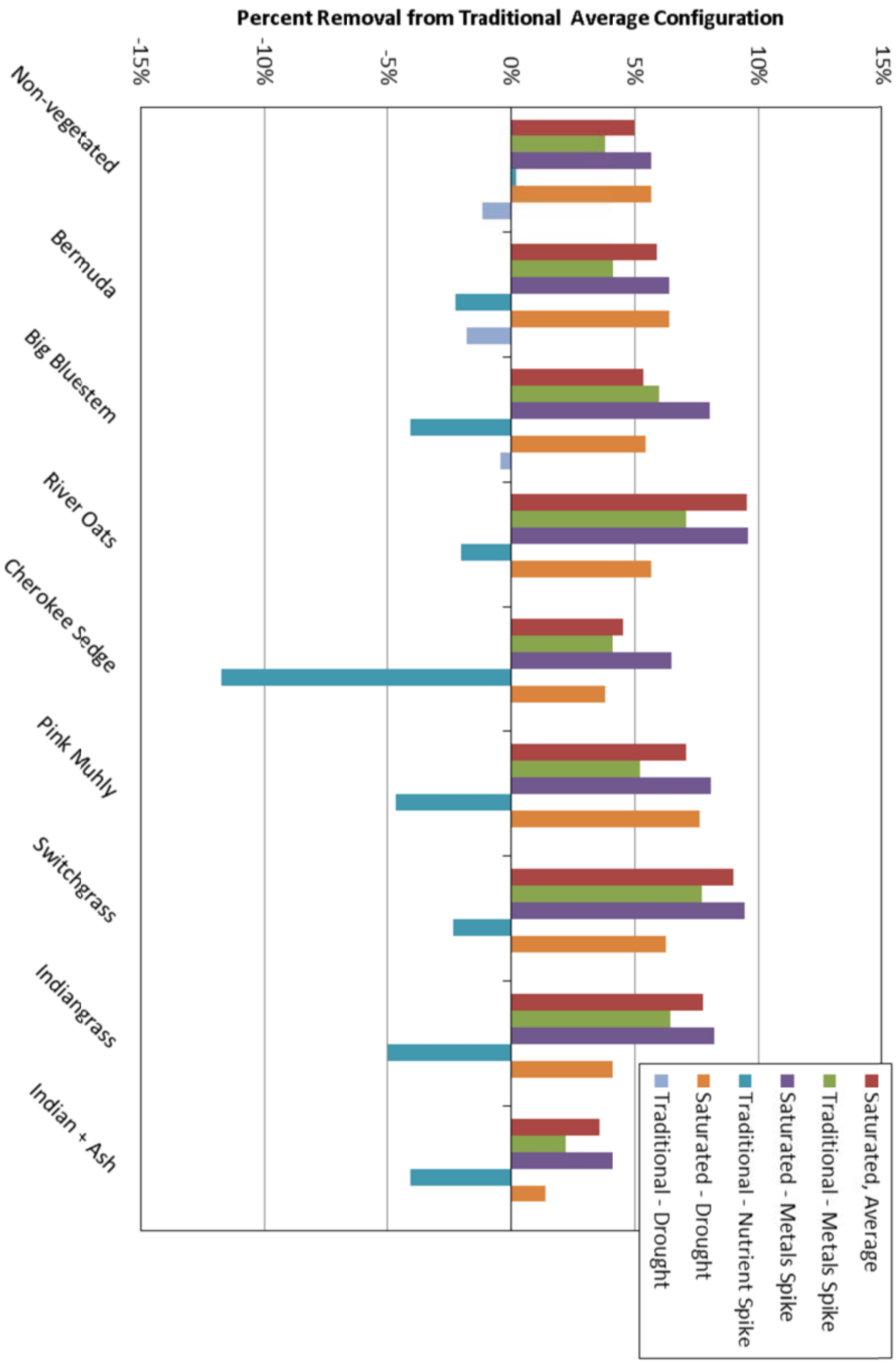

Figure 25: Copper removal as compared to the traditional configuration dosed with average synthetic stormwater.

Lead

Results for lead removal in all configurations were greater than 97%, with no statistically significant differences observed in plant species or column configuration (Figure 26 through Figure 29). Concentrations were reduced from 250 ppb to 4 ppb on average across all columns during average synthetic stormwater dosing with one maximum effluent concentration of 18 ppb in one saturated Cherokee Sedge column.

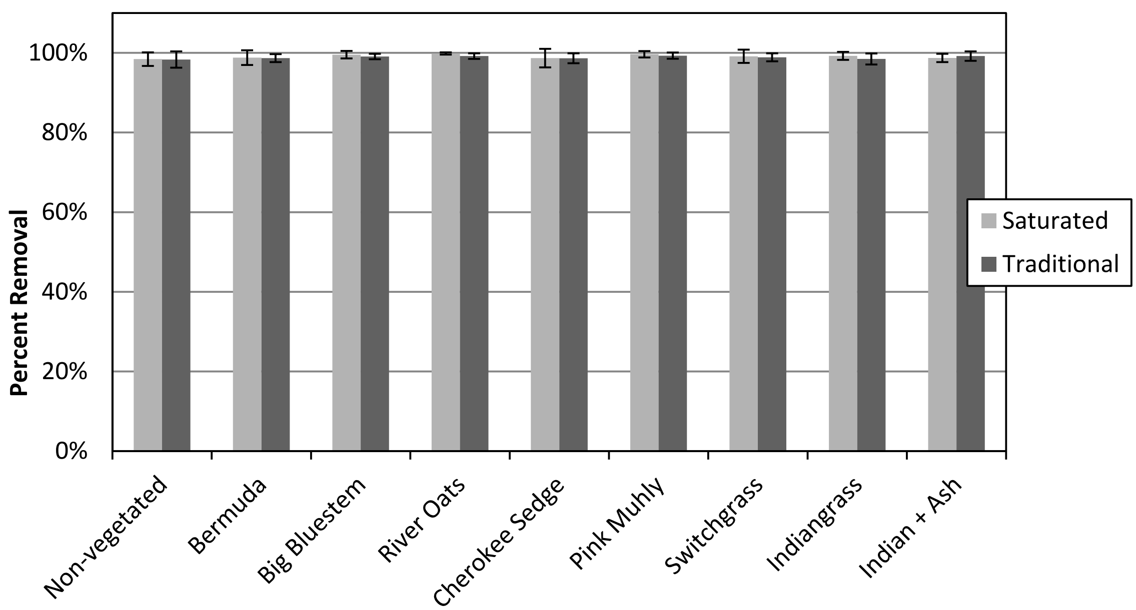

Figure 26: Lead removal by plant species for columns dosed with average synthetic stormwater.

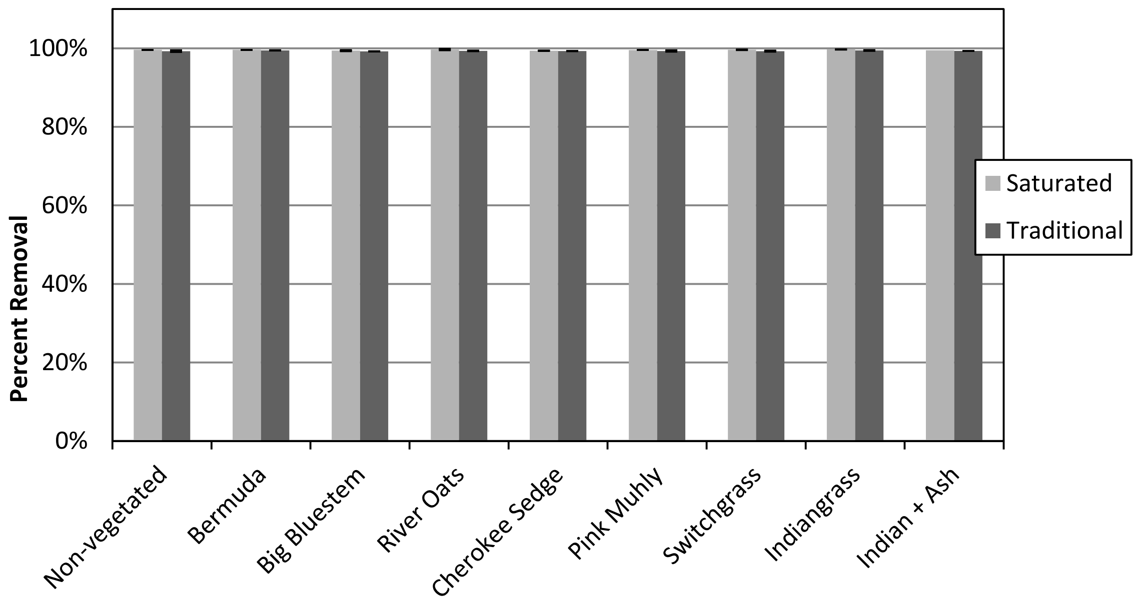

Figure 27: Lead removal by plant species for columns dosed with metal spiked synthetic stormwater.

Lead concentrations were reduced from 730 ppb to 6 ppb on average across all columns after the metals spiked synthetic stormwater dosing. Maximum effluent concentrations of 18 ppb were observed in saturated Indiangrass with biomass ash columns.

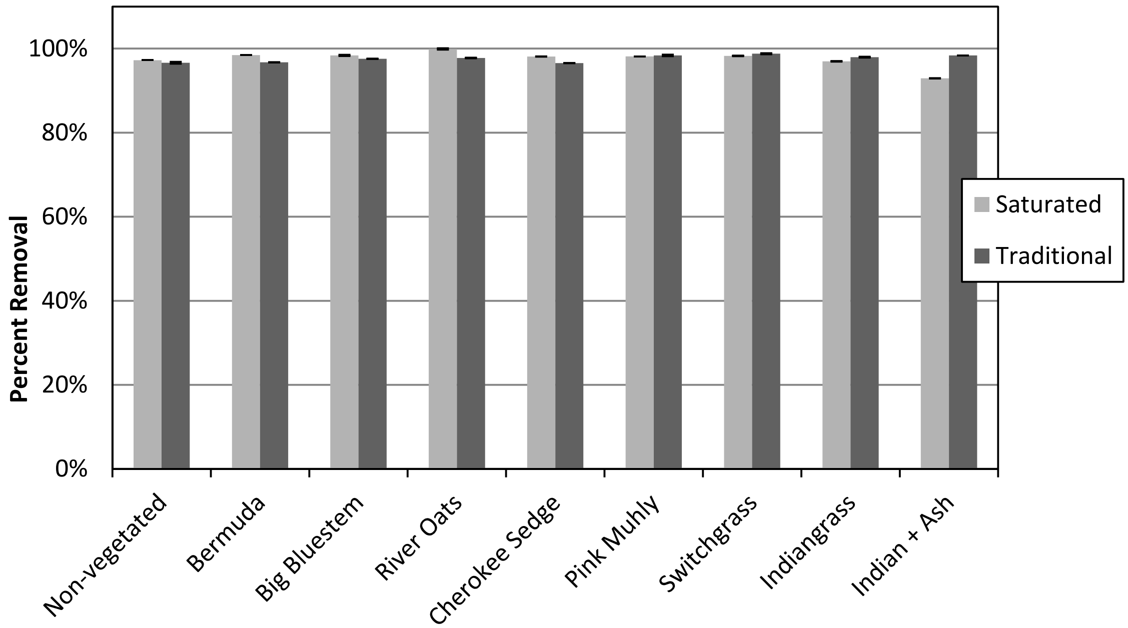

Figure 28: Lead removal by plant species for columns dosed with nutrient spiked synthetic stormwater conditions.

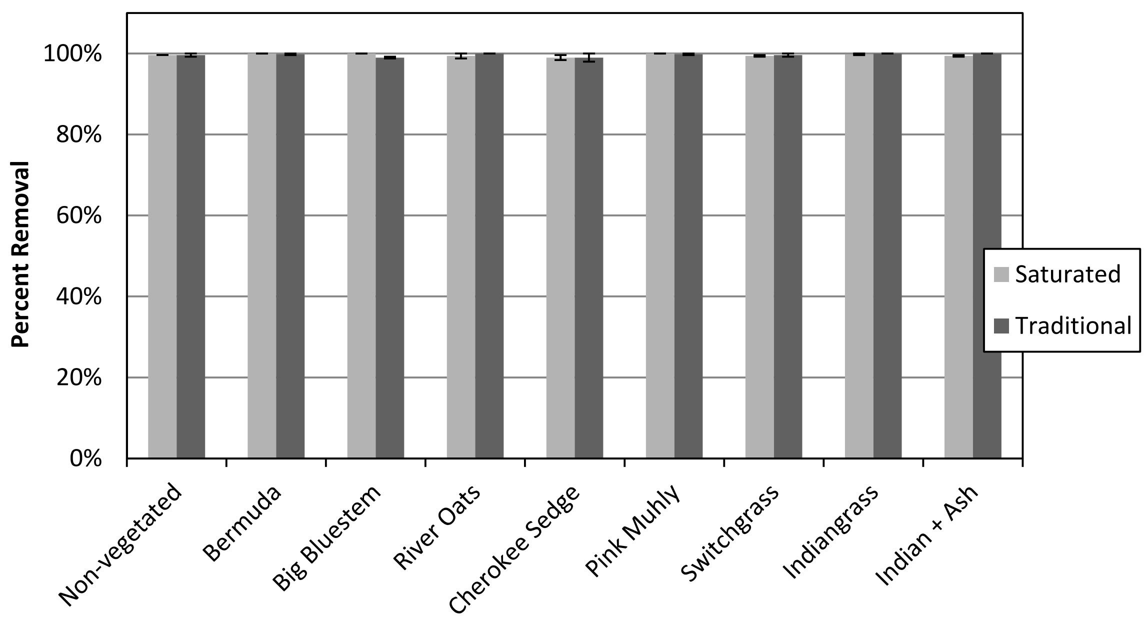

Figure 29: Lead removal by plant species for columns dosed with average synthetic stormwater after two weeks of drought conditions.

A comparison of all enhancements shows differences within ±2% of the traditional configuration with average stormwater (Figure 30). Differenced between the saturated and traditional configuration were not considered statistically significant ($p > 0.05$). A slight decrease in performance was observed in the nutrient spiked conditions ($p < 0.01$ in saturated and $p < 0.0006$ in traditional).

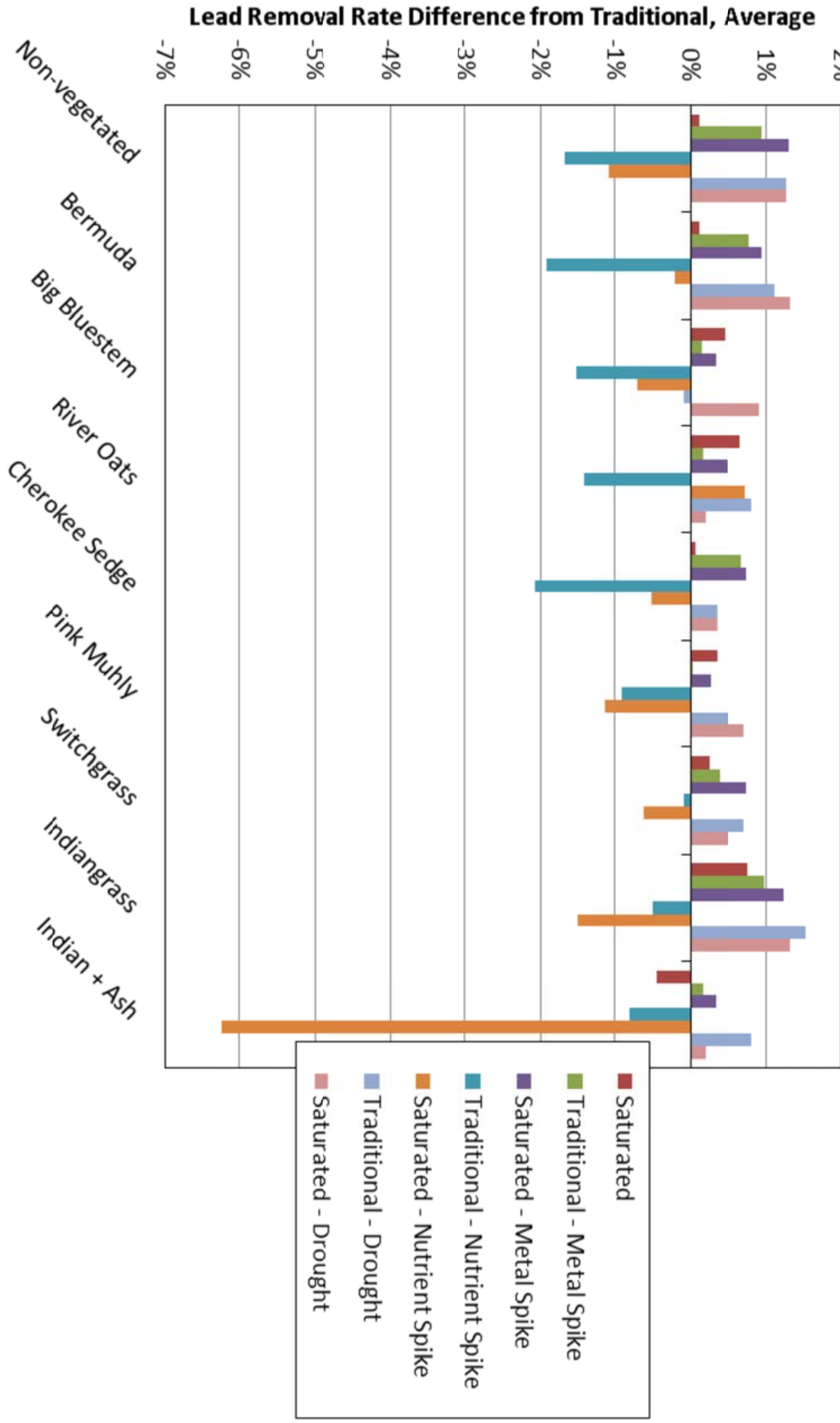

Figure 30: Lead removal as compared to the traditional configuration with average synthetic stormwater.

Zinc

Zinc showed the greatest variation in removal for the three heavy metals measured. This is consistent with the column studies performed by Davis et al. (2001), which found zinc to have the lowest sorption to a sandy loam soil at neutral pH. Average removal for traditional columns ranged from 67% to 87%, while removal in the saturated columns ranged from 81% to 93% (Figure 31).

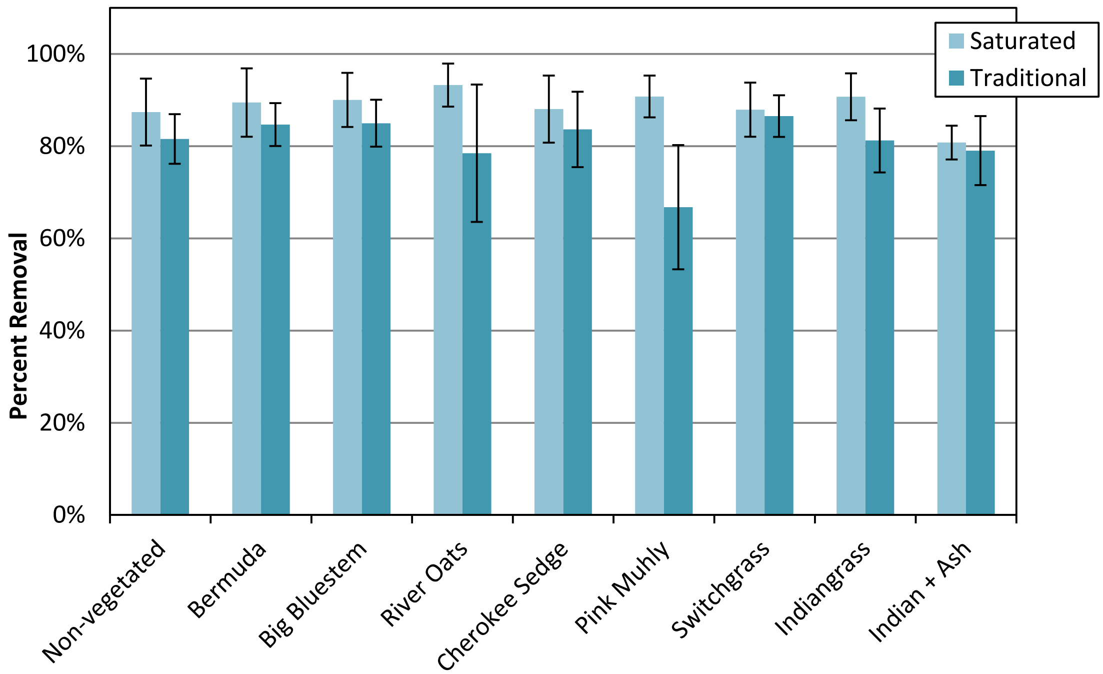

Figure 31: Zinc removal by plant species for columns dosed with average synthetic stormwater.

Consistent with the trends for copper and lead, zinc also showed increased removal when heavy metal concentrations were spiked (Figure 32). In this condition, removals were greater than 94% and 97% in the traditional and saturated conditions, respectively.

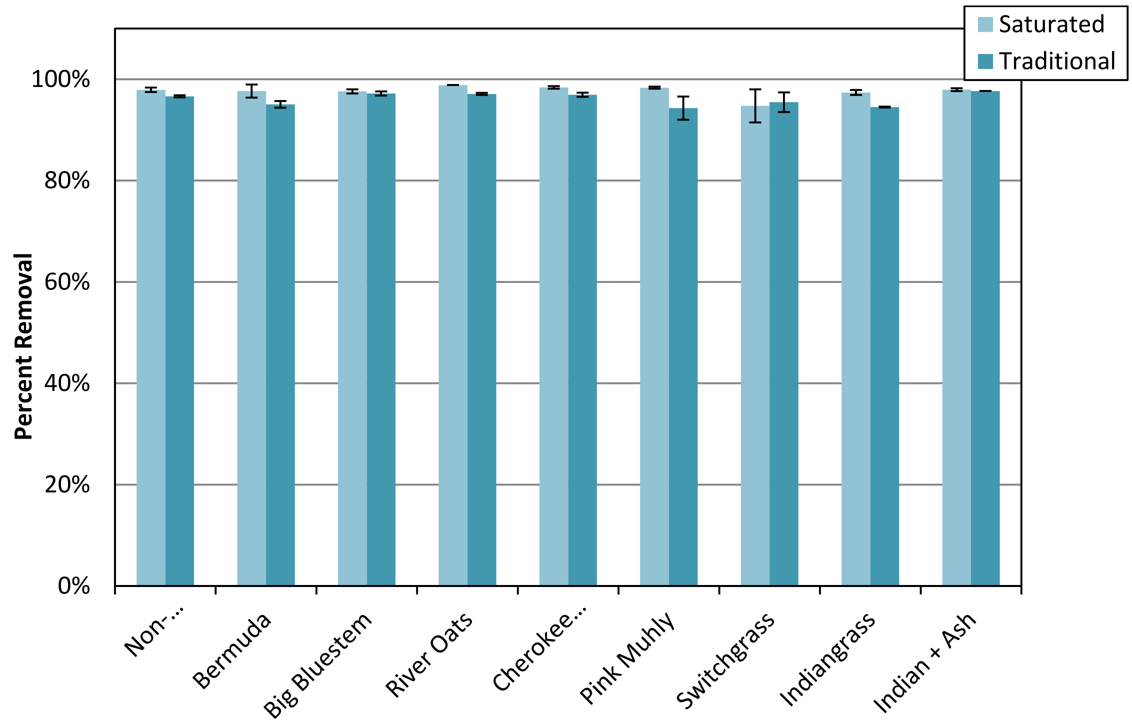

Figure 32: Zinc removal by plant species for columns dosed with metal spiked synthetic stormwater.

High variation was observed in the zinc removal with nutrient spiked stormwater and average stormwater after a drought period (Figure 33 and Figure 34). While the addition of soluble phosphorus may have caused increased precipitation of lead phosphate and thus immobilization in the soil, one study showed the increase of leachable zinc from heavy metal contaminated soil media (Fang et al. 2012).

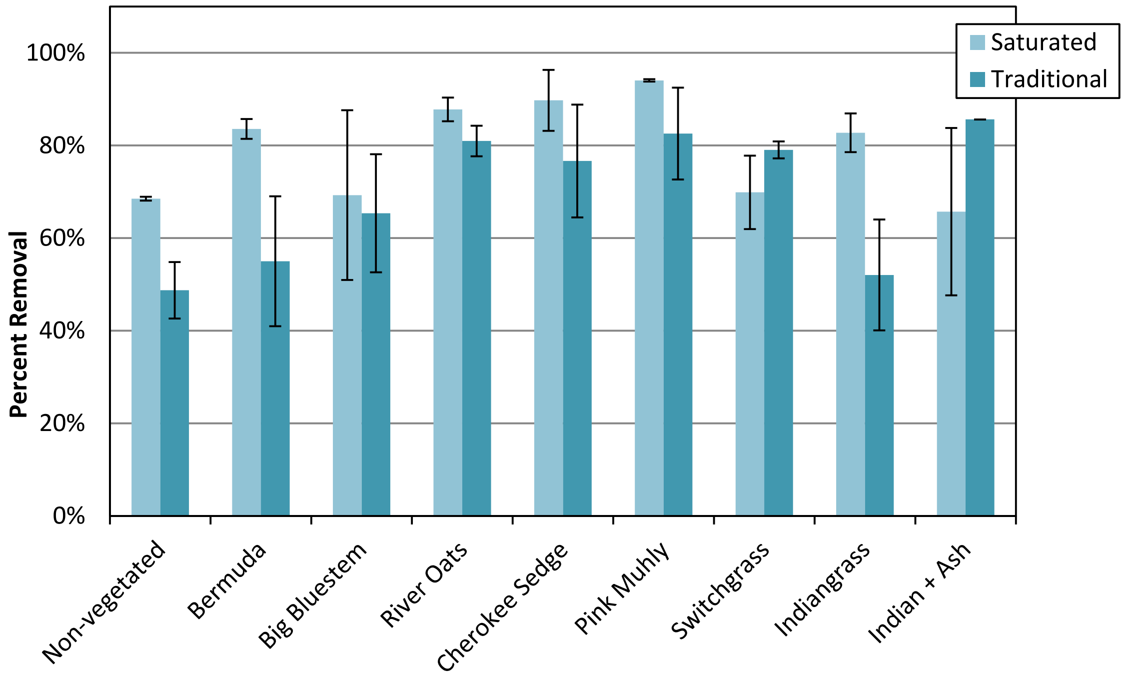

Figure 33: Zinc removal by plant species for columns dosed with nutrient spiked synthetic stormwater.

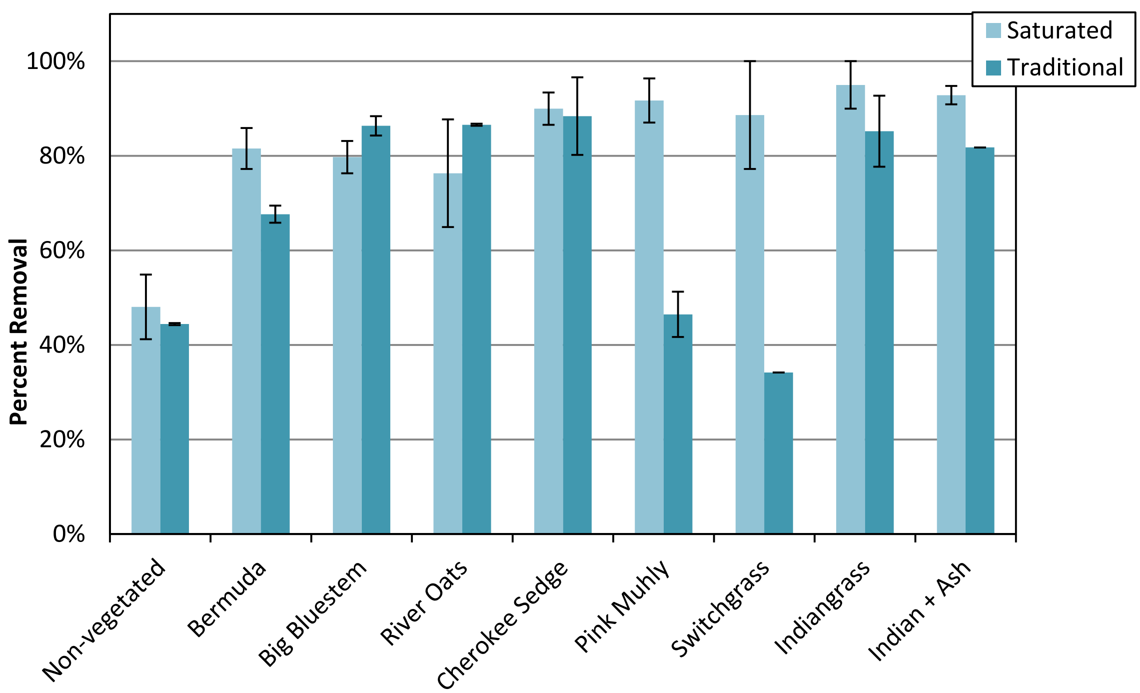

Figure 34: Zinc removal by plant species for columns dosed with average synthetic stormwater after two weeks of drought conditions.

The lowest removal extent of zinc (34%) was observed in a traditional Switchgrass column after a two week drought period. When comparing all zinc removals to that of the traditional configuration with average stormwater, trends observed for copper and lead remain consistent with zinc (Figure 35) with highest removal observed in the saturated, metals spiked conditions. Zinc results exhibited far greater variability when compared to lead and copper, making removal trends less evident.

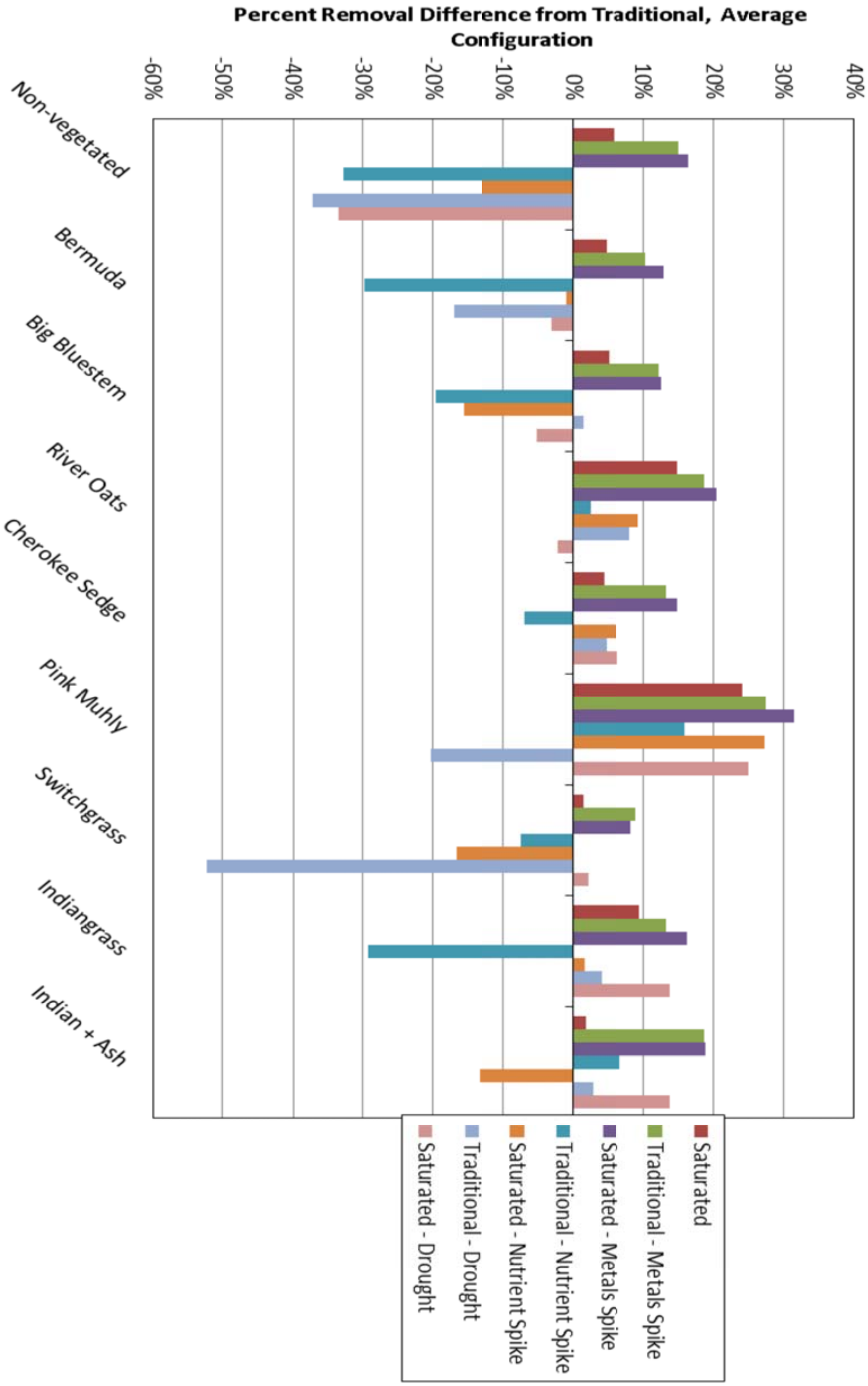

Figure 35: Zinc removal as compared to the traditional configuration with average synthetic stormwater.

Turbidity

Although suspended solids were not added to the synthetic stormwater, noticeable differences in the turbidity of samples were observed upon collection. Turbidity was measured as a surrogate for total suspended solids as gravimetric analysis would have required large volumes of water for the low concentrations observed. Data for all but the first sampling event are shown in Figure 36 through Figure 39 below. Inflow turbidity was measured as 1.11 ± 0.37 NTU except in the case of the metals spiked stormwater which was 4.68 NTU.

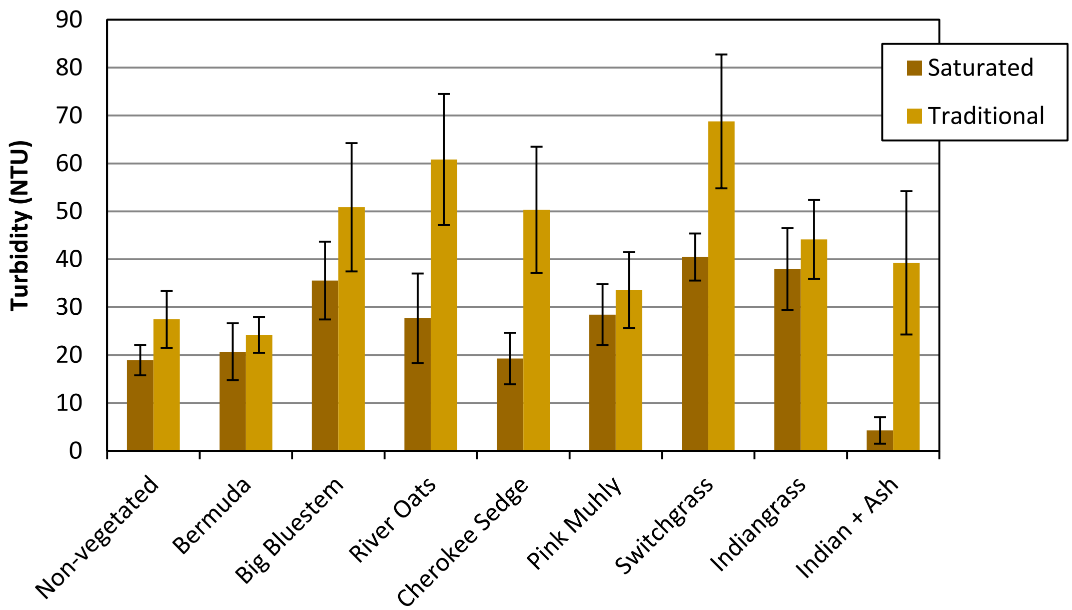

Figure 36: Turbidity by plant species for columns dosed with average synthetic stormwater.

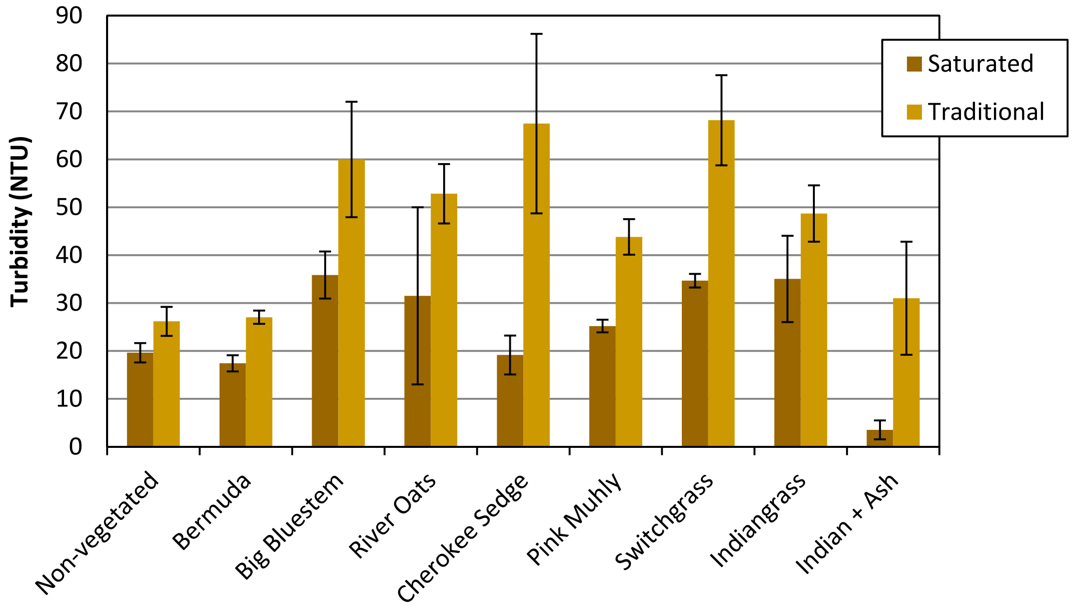

Figure 37: Turbidity by plant species for columns dosed with metals spiked synthetic stormwater.

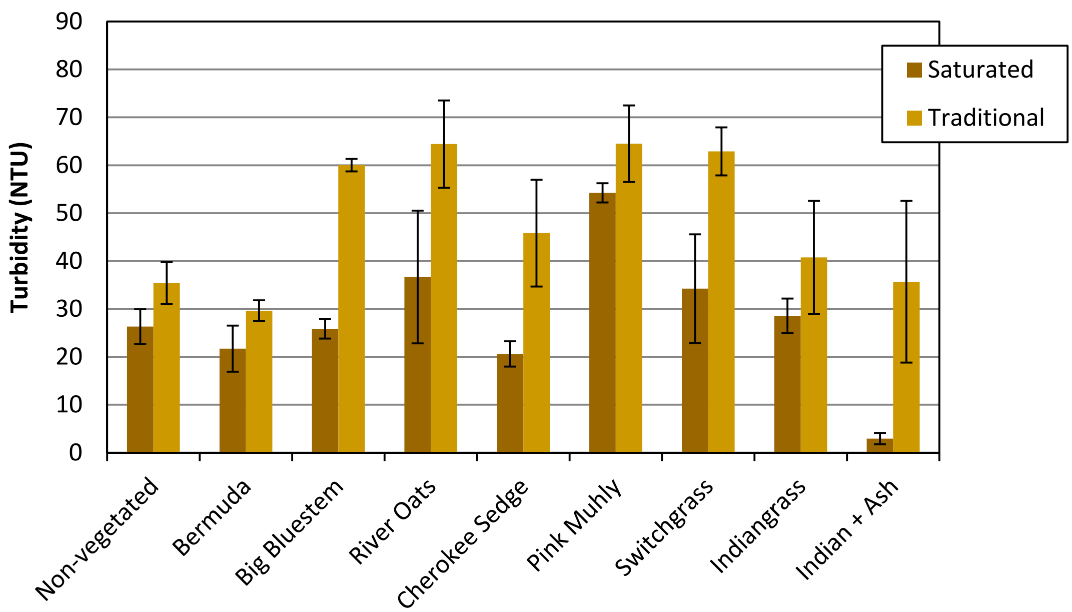

Figure 38: Turbidity by plant species for columns dosed with nutrient spiked synthetic stormwater.

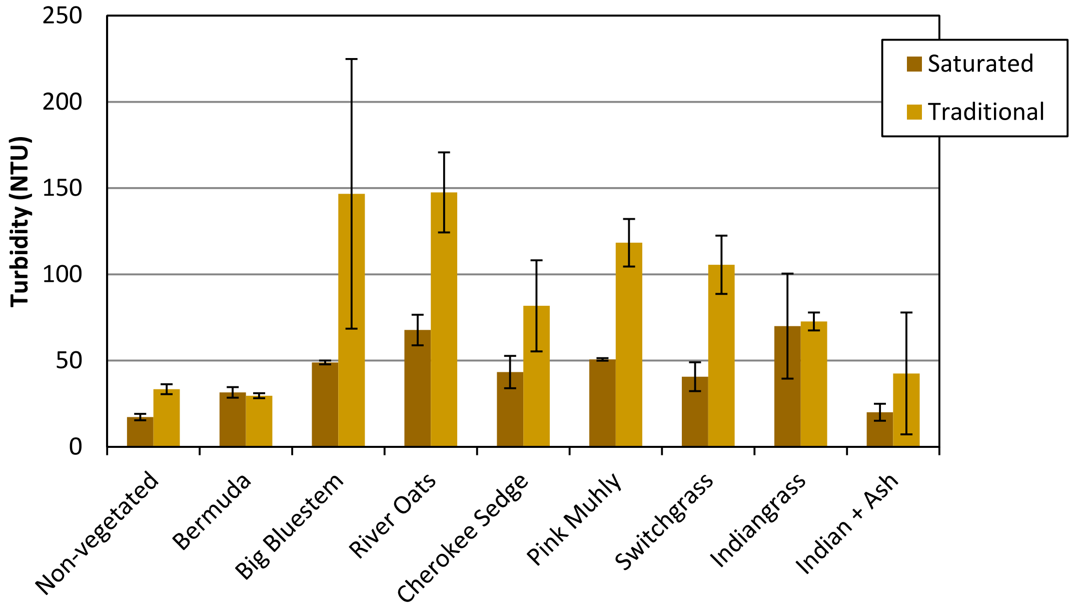

Figure 39: Turbidity by plant species for columns dosed with average synthetic stormwater after two weeks of drought conditions.

For all sampling events, the saturated configuration resulted in less turbidity in the effluent than the traditional configuration. This is attributable to decreased velocities created by the saturated zone, which allows fine solids to settle and filter from the effluent. Columns configured with a saturated layer and an ash/sand mixture consistently yielded very low turbidity results.

pH

Effluent pH was measured immediately after sample collection. Influent pH was adjusted to 7.0. The pH typically remained just less than 7.0 in all cases except those that included biomass ash (Figure 40 through Figure 43). The pH exceeded 7.0 consistently in biomass columns with a saturated zone.

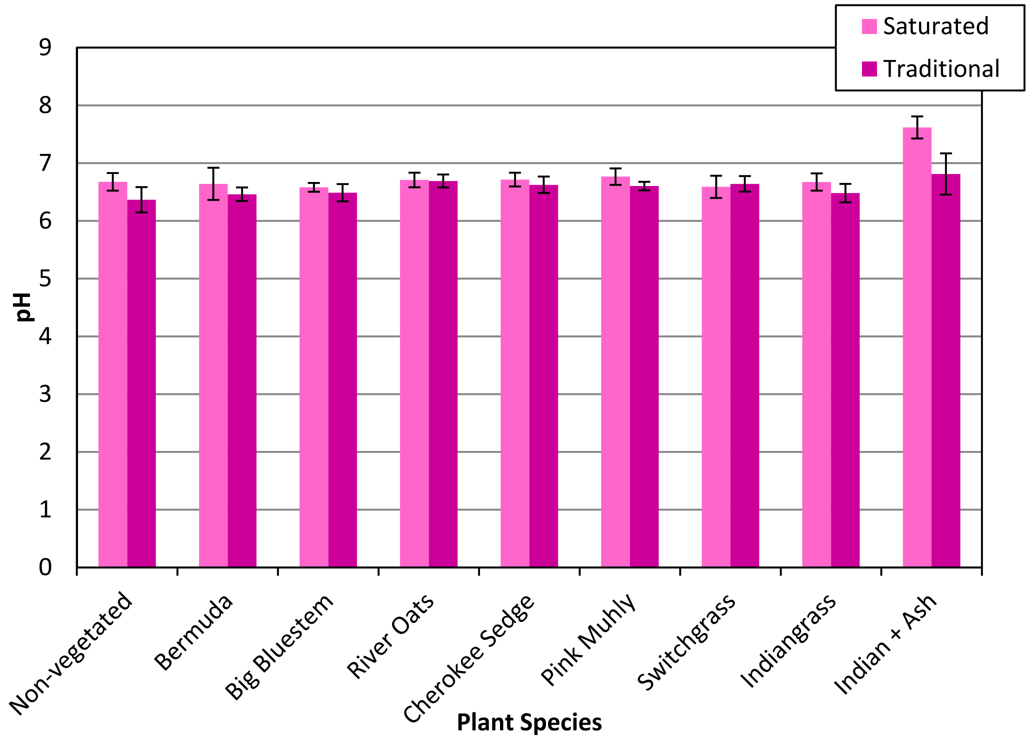

Figure 40: pH of treated average synthetic stormwater.

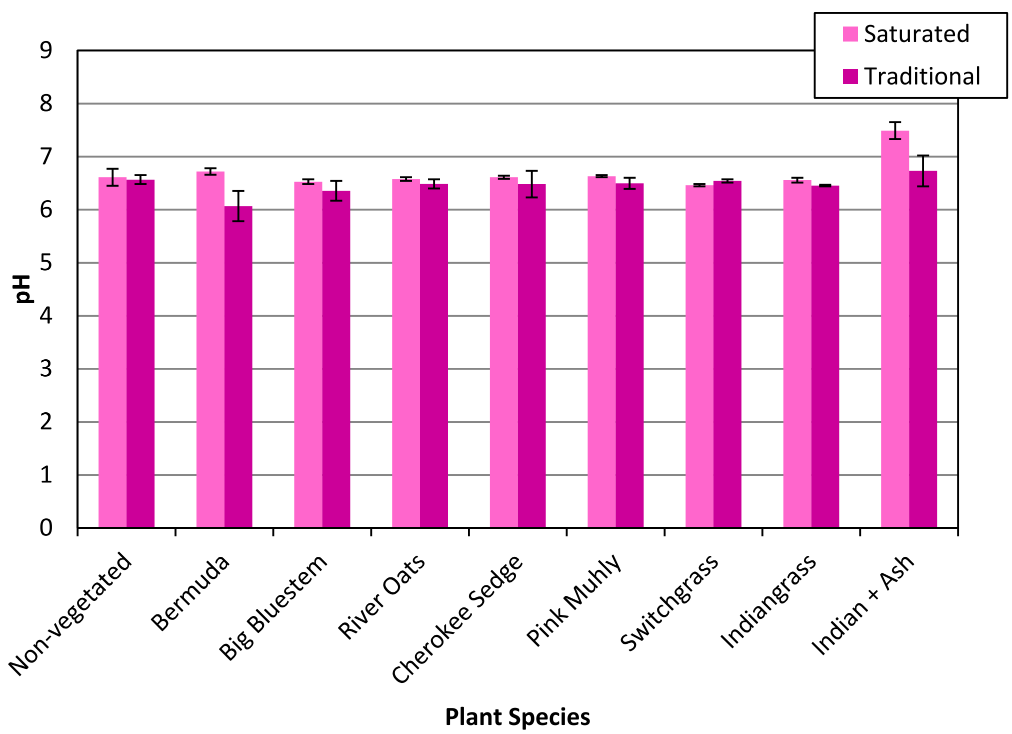

Figure 41: pH of treated metals spiked synthetic stormwater.

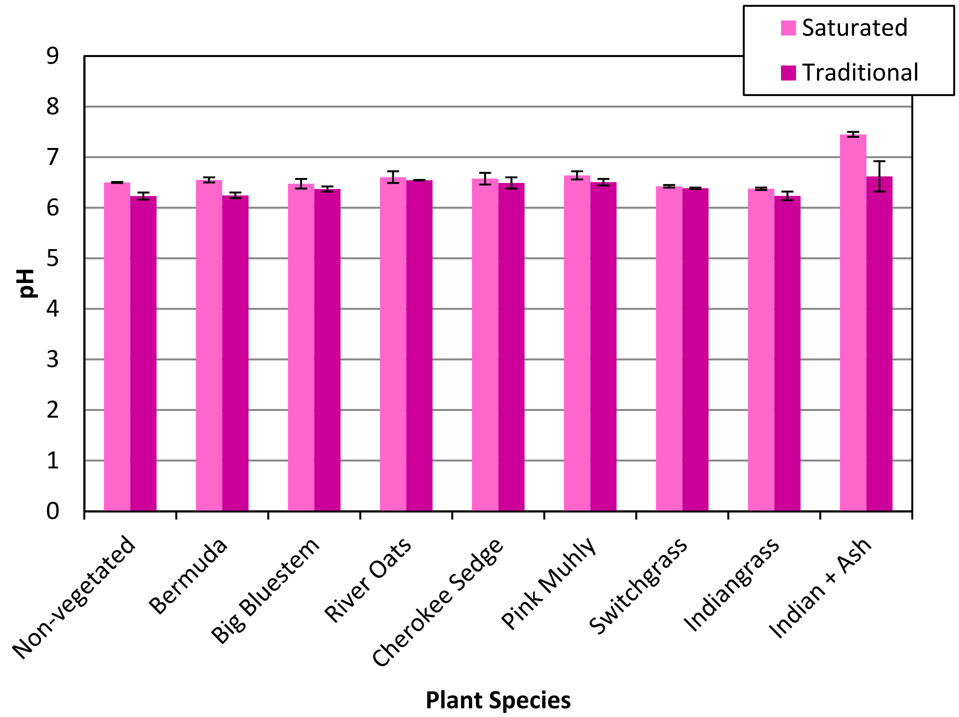

Figure 42: pH of treated nutrient spiked synthetic stormwater.

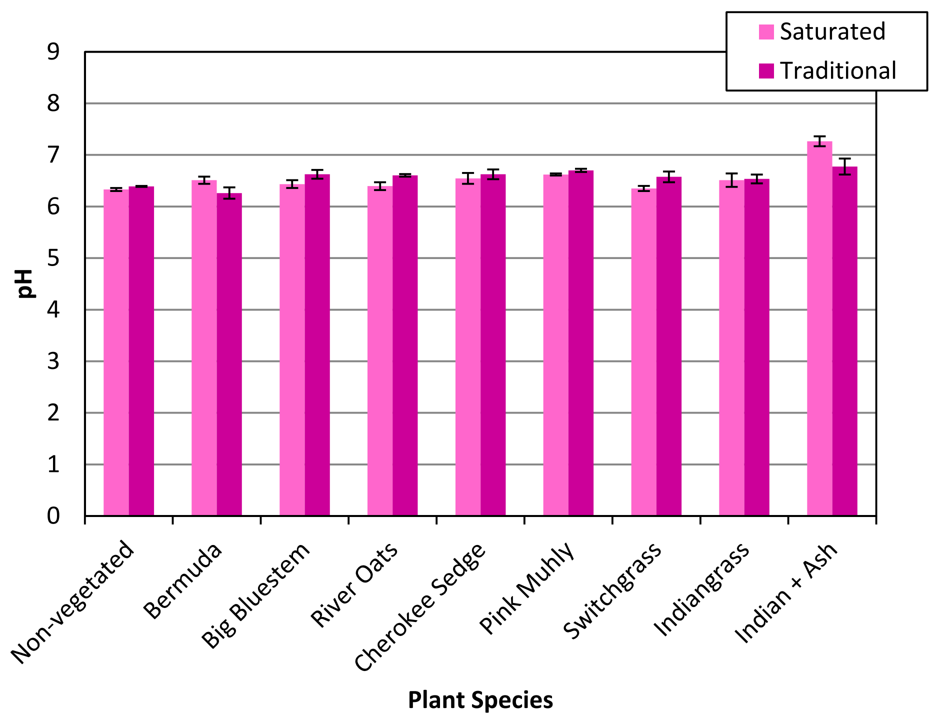

Figure 43: pH of treated average synthetic stormwater after two weeks of drought.

When compared to Indiangrass columns without ash, the observed increase of pH in the presence of biomass ash was statistically significant in both the traditional and saturated configurations ($p < 0.006$ and $p < 0.0005$ respectively). The increase in pH was likely not large enough to enhance precipitation of metals from solution through complexation with hydroxides.

Plant Growth

Grasses at the Canton, GA sand filter were planted on May 4, 2014; however, mowing took place in early June. Reported heights are considered from approximately 3 inch height on June 21, 2014 until a final height measurement on August 13, 2014 along with measured heights of greenhouse grown grasses (Table 5). Measurements for greenhouse grown grasses were taken on October 16, 2014.

Table 5. Root depth and height measurements for column and field plants.

	Root depth Saturated (inches)[a]	Root depth Traditional (inches)[a]	Plant Height, Saturated (inches)[b]	Plant Height, Traditional (inches)[b]	Plant Height, Field (inches)[c]
Bermuda	12	10	12	12	n/a
Big Bluestem	28	28	56.5 ± 2.5	38 ± 11	59
River Oats	15	16	41.5 ± 5.5	37 ± 2	16
Cherokee Sedge	22	13	35 ± 3	31.5 ± 0.5	14
Pink Muhly	12	12	48	42.5 ± 1.5	19
Switchgrass	28	28	48 ± 1	48 ± 1	39 ± 2.5
Indiangrass	22	12	53 ± 19	52 ± 12	57 ± 7
Indian + Ash	24.5	28	64	63	n/a

Notes:

a - Maximum soil media depth was 28 inches with 0 to 12 inches of planting soil, 12 to 22 inches sand or sand/carbon source mixture, and 22 to 28 inches drainage gravel. Measurement after six months of growth (April to October 2014)

b – Measurement after six months of growth (April to October 2014)

c – Measurement after two months of summer growth (June through August 2014)

Since the greenhouse grasses had approximately four months more time for growth, the heights are generally lower for the field planted varieties. Big Bluestem and

Indiangrass seemed to reach comparable heights, while all others were shorter at comparable lengths of growth time.

Soil was shaken loose from root systems to determine the greatest root depths in the entire soil column. Root depth varied significantly in the grasses, with roots from the Big Bluestem and Switchgrass penetrating completely and vigorously through the gravel layer. Indiangrass and Cherokee Sedge showed a significantly greater root depth in the saturated configuration than traditional. Indiangrass also seemed to penetrate deeper into the sand layer and even through the gravel in the presence of biomass ash. This root density may explain some variation in pollutant uptake in accordance with previous studies on plant characteristics (Read et al. 2010). Field constructed biofilters will contain much greater depths of planting media which may lead to growth remaining in the planting soil rather than growing through the sand layer.

Summary

Nutrient removal for all four experiments were averaged to estimate the performance of each grass species across all conditions (Figure 44 and Figure 45). Heavy metal removal was excluded as variation among plant species was not evident. All native grasses performed more efficiently in terms of nitrogen removal as compared to control non-vegetated and Bermuda grass columns.

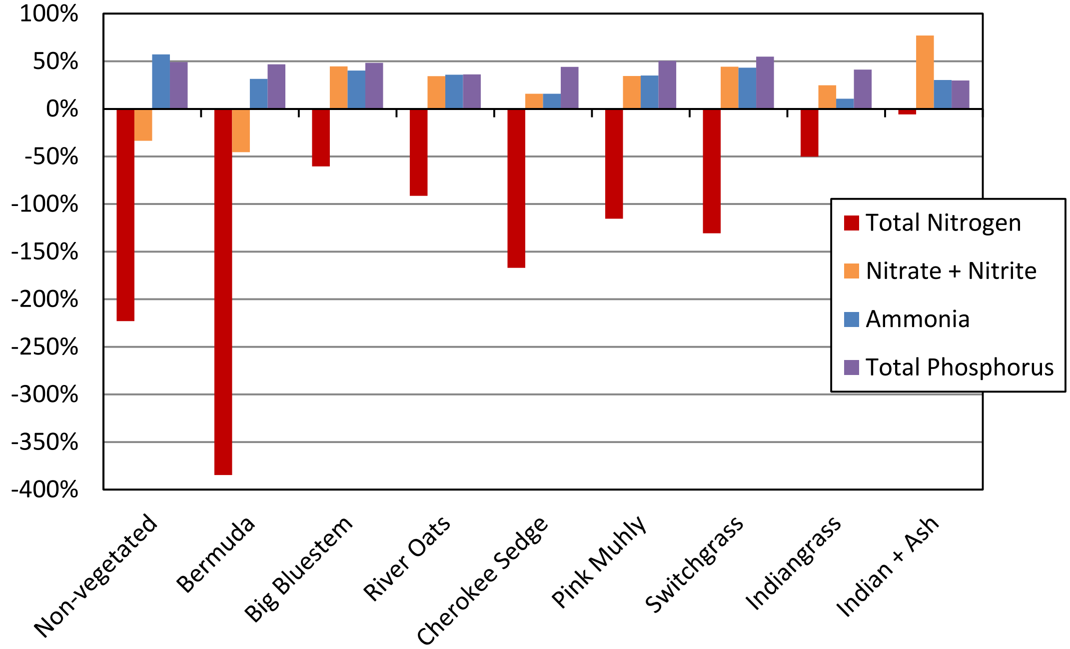

Figure 44: Average nutrient removal across all expirements in the traditional configurations.

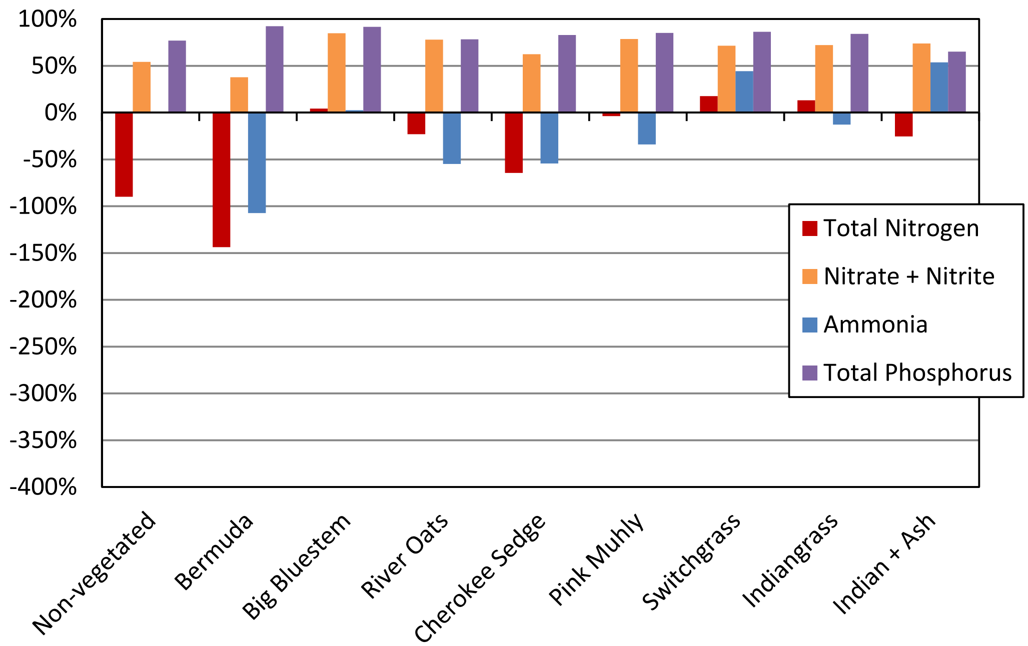

Figure 45: Average nutrient removal across all experiments in saturated configurations.

Big Bluestem

Among the six native grasses tested, Big Bluestem was among the top three performing grasses in the saturated condition and top two in the traditional condition based on average removal across all experiments. This same trend applies to ammonium removal. In terms of NOx, Big Bluestem had the top removal in both traditional (45%) and saturated (85%) conditions across all experiments. Big Bluestem also had a maximum total phosphorus removal of 92% in the saturated condition. In both column configurations, Big Bluestem roots penetrated the entire depth of the soil media.

River Oats

River Oats had medium to low removal of nutrients in comparison to other species studied. It had the lowest total phosphorus removal of all native species on average. River Oats leached total nitrogen in both saturated and traditional conditions (-23% and -91% respectively). NOx removal was 34% in the traditional and 78% in the saturated conditions which were in the middle range of all species. River Oats had shallow root systems in the columns extending slightly deeper than the topsoil layer with many thick roots along the inner perimeter of the column.

Cherokee Sedge

Cherokee sedge had the lowest removal of total nitrogen and NOx across all experiments. It also showed the second lowest removal of phosphorus (83%), just behind River Oats in the saturated condition. This sedge had some of the shallowest and thinnest diameter roots, particularly in the traditional condition, which may help explain low nutrient uptake.

Pink Muhly

Pink Muhly removal of all nutrients typically ranked in the middle of all native species. On average across all experiments, Pink Muhly leached total nitrogen in both traditional and saturated conditions (-116% and -4% respectively). Total phosphorus removal was 50% in the traditional columns and 85% in the saturated columns. Pink Muhly had the shallowest root system of any native species within the columns.

Switchgrass

Switchgrass typically had very high performance with all nutrients when compared to other species. Switchgrass roots penetrated the entire depth of the column with dense roots in the lower sand and gravel of the traditional column. In the traditional configuration, Switchgrass showed one of the highest total nitrogen leachate extents with -131% removal; however, it had the maximum total nitrogen removal of 18% in the traditional configuration. This may be due to the difference in root density between the saturated and traditional columns in the lower portions of the filter. Switchgrass was the top total phosphorus remover in the traditional configuration (55%) and second in the saturated (86%).

Indiangrass

Lastly, Indiangrass was among the top two performers of total nitrogen (-50% traditional and 13% saturated) and top three performers of NO_x (25% traditional and 72% saturated) across all experiments. Indiangrass removed ammonia at some of the lowest percentages. While generally more shallow than Switchgrass and Big Bluestem, roots of Indiangrass were very dense in the planting soil layer as compared to Cherokee Sedge and Pink Muhly.

CHAPTER 5

CONCLUSIONS

On average across all experiments, total nitrogen was removed at the highest percentage of 18% with Switchgrass and was leached at an average of 143% with Bermuda grass when both were grown with a saturated layer in the soil column. These results demonstrated the significant differences in nitrogen removal based on the vegetation type. Among these six native species, top recommendations include Big Bluestem and Switchgrass for consistent, high removal extents. Saturation increased the removal of NO_x in combination with any of the plants used in this study. Saturation also increased the removal of total phosphorus, typically to greater than 80% removal. Copper, lead, and zinc experienced minimum removal extents of 82%, 97%, and 34%, with highest removal in the saturated configuration. Metals removal was not correlated to plant species which indicated that sorption to the soil media was likely the primary mechanism responsible for removal. Biomass ash performance varied greatly through all experiments, with some high nutrient removals observed in the aerobic condition. Further field study should be performed to verify these results and eliminate some of the inherent errors that column studies allow.

Further Study

Biofilters were monitored July through October which constitutes approximately half of the growing season. Long term studies of biofiltration configurations during all seasons will be necessary to determine overall efficiency of plant species. Additionally, plants should be allowed a long term establishment to account for roots growing through the depth of the filter over time. Field studies are also suggested to account for the increased depth of soil media from a column configuration and the possible error associated with short circuiting in the columns. In many of the species, thick roots formed along the edge of the column allowing water to flow along these macropores rather than through the soil perhaps contributing to error in these experiments. Lastly, soil with a lower organic content may be necessary as organic nitrogen leachate was common during all experiments.

APPENDIX A

PHOTO LOG

Figure 46: Constructed column of 8-inch diameter PVC, a 1/2 inch outlet, and clamped rubber end cap.

Figure 47: Mixing of natural sand with 5% hardwood mulch by hand in wheel barrow.

Figure 48: Natural sand and 5% biomass ash mixture.

Figure 49: Constructed Palram 8 ft. by 12 ft. greenhouse.

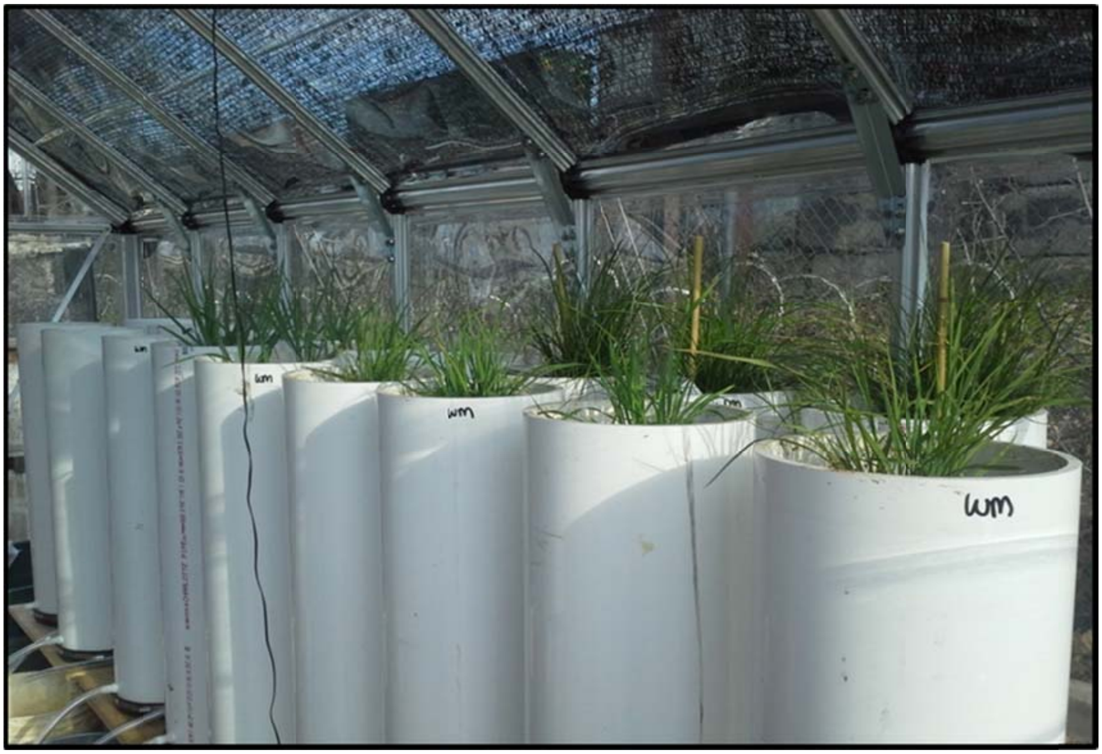

Figure 50: Planting of Big Bluestem (front), and Switchgrass (left) on April 1, 2014.

Figure 51: Planting of River Oats (front row, left), Pink Muhly (front row, right), and Cherokee Sedge (back row, right) on April 1, 2014.

Figure 52: Greenhouse on sampling day showing columns, tubing, sampling buckets, and stormwater mixing tank.

Figure 53: Grass planted at the Canton, GA filter site on May 8, 2014.

Figure 54: Bermuda grass in the traditional configuration on October 16, 2014.

Figure 55: Inside of traditional, Bermuda grass column.

Figure 56: Bermuda grass in the saturated configuration on October 16, 2014.


Figure 57: Inside of saturated, Bermuda grass column.

Figure 58: Big Bluestem in the traditional configuration on October 16, 2014.

Figure 59: Inside of traditional, Big Bluestem column.

Figure 60: Big Bluestem in the saturated configuration on October 16, 2014.

Figure 61: Inside of saturated, Big Bluestem column.

Figure 62: River Oats in the traditional configuration on October 16, 2014.

Figure 63: Inside of traditional, River Oats column.

Figure 64: River Oats in the saturated configuration on October 16, 2014.

Figure 65: Inside of saturated, River Oats column.

Figure 66: Cherokee Sedge in the traditional configuration on October 16, 2014.

Figure 67: Inside of traditional, Cherokee Sedge column.

Figure 68: Cherokee Sedge in the saturated configuration on October 16, 2014.

Figure 69: Inside of saturated, Cherokee Sedge column.

Figure 70: Pink Muhly in the traditional configuration on October 16, 2014.

Figure 71: Inside of traditional, Pink Muhly column.

Figure 72: Pink Muhly in the saturated configuration on October 16, 2014.

Figure 73: Inside of saturated, Pink Muhly column.

Figure 74: Switchgrass in the traditional configuration on October 16, 2014.

Figure 75: Inside of traditional, Switchgrass column.

Figure 76: Switchgrass in the saturated configuration on October 16, 2014.

Figure 77: Inside of saturated, Switchgrass column.

Figure 78: Indiangrass in the traditional configuration on October 16, 2014.

Figure 79: Inside of traditional, Indiangrass column.

Figure 80: Indiangrass in the saturated configuration on October 16, 2014.

Figure 81: Inside of saturated, Indiangrass column.

Figure 82: Indiangrass in the traditional configuration with ash on October 16, 2014.

Figure 83: Inside of traditional, Indiangrass column with ash.

Figure 84: Indiangrass in the saturated configuration with ash on October 16, 2014.

Figure 85: Inside of saturated, Indiangrass column with ash.

Figure 86: Big Bluestem at the Canton filter site on September 13, 2014.

Figure 87: River Oats at the Canton filter site on September 13, 2014.

Figure 88: Cherokee Sedge at the Canton filter site on September 13, 2014.

Figure 89: Pink Muhly at the Canton filter site on September 13, 2014.

Figure 90: Switchgrass at the Canton filter site on September 13, 2014.

Figure 91: Indiangrass at the Canton filter site on September 13, 2014.

APPENDIX B

COLLECTED DATA

Table 6: Column ID Definitions

Plant Species	**Common Name**	**Saturated**	**Traditional**
Non-vegetated	Non-vegetated	BL2-S, BL4-S	BL1, BL3
Cynodon dactylon	Bermuda Grass	BM2-S, BM4-S	BM1, BM3
Andropogon gerardii	Big Bluestem	AG1-S, AG3-S	AG2, AG4
Chasmanthium latifolium	River Oats	RO1-S, RO3-S	RO2, RO4
Carex cherokeensis	Cherokee Sedge	CS2-S, CS4-S	CS1, CS3
Muhlenbergia capillaris	Pink Muhly	PM1-S, PM3-S	PM2, PM4
Panicum virgatum	Switchgrass	SW1-S, SW4-S	SW2, SW3
Sorghastrum nutans	Indiangrass	IG1-S, IG4-S	IG2, IG3
Sorghastrum nutans	Indiangrass + Ash	IGA2-S, IGA3-S	IGA1

Table 7: Measurements of Total Nitrogen (mg N/L)

Stormwater Type	Average Stormwater					Metal Spike	Nutrient Spike	After Drought
Date	7/7/14	7/21/14	8/4/14	8/18/14	Average	9/1/14	9/22/14	10/7/14
BL2-S	1.27	3.81	6.41	15.47	6.74	12.69	26.68	11.95
BL4-S	1.81	3.16	4.29	13.64	5.72	9.32	10.58	15.35
BM2-S	6.47	6.33	5.47	13.55	7.95	13.95	17.16	20.05
BM4-S	5.84	1.77	1.72	14.43	5.94	17.49	21.87	20.10
AG1-S	1.94	1.42	1.76	2.50	1.91	9.39	9.04	6.95
AG3-S	1.15	1.43	4.38	3.99	2.74	4.85	9.56	6.86
RO1-S	1.74	4.76	8.67	6.68	5.46	4.95	7.85	8.74
RO3-S	2.78	5.42	7.42	8.12	5.93	7.74	14.93	8.80
CS2-S	2.70	5.07	6.58	6.83	5.30	7.79	14.67	13.48
CS4-S	4.62	4.54	4.82	9.24	5.80	12.31	13.52	12.65
PM1-S	3.67	7.13	7.05	5.46	5.83	6.84	10.72	2.20
PM3-S	3.61	3.54	7.19	5.00	4.83	7.39	10.07	8.11
SW1-S	2.56	2.60	2.35	7.35	3.71	4.27	12.57	2.81
SW4-S	1.73	6.22	5.96	2.39	4.08	5.78	18.50	2.76
IG1-S	4.12	1.16	2.54	5.75	3.39	5.14	13.13	9.33
IG4-S	2.55	2.01	4.48	2.71	2.94	4.83	11.37	1.73
IGA2-S	n.a.	2.70	5.90	4.14	4.25	5.72	12.32	7.41
IGA3-S	n.a.	6.03	5.94	5.59	5.85	11.91	13.26	6.57
BL1	14.81	2.72	4.05	25.11	11.67	19.95	27.31	21.97
BL3	13.91	2.19	2.91	23.18	10.55	21.24	6.81	33.90
BM1	8.50	2.51	4.95	24.35	10.08	18.83	30.31	27.55
BM3	14.50	4.49	6.42	24.11	12.38	73.81	33.00	30.50
AG2	4.95	2.82	6.32	7.46	5.39	7.65	16.50	1.53
AG4	6.54	8.66	7.18	23.24	11.40	14.98	20.56	14.61
RO2	9.69	10.90	5.55	18.26	11.10	12.91	22.04	9.41
RO4	6.72	11.01	5.19	13.91	9.21	12.49	25.02	7.99
CS1	11.02	6.77	9.92	12.50	10.05	20.98	21.10	6.88
CS3	6.06	10.56	8.99	13.74	9.84	8.31	66.18	22.80
PM2	8.71	2.63	4.24	11.84	6.85	16.92	19.04	8.35
PM4	7.22	3.40	5.59	16.22	8.11	18.90	22.20	14.73
SW2	4.89	8.15	7.29	7.31	6.91	16.81	19.10	12.51
SW3	4.75	2.49	4.68	6.74	4.66	16.30	25.07	19.30
IG2	12.55	1.96	1.60	13.04	7.29	0.53	37.93	11.40
IG3	9.53	2.05	4.03	12.31	6.98	3.81	21.20	11.56
IG-A1	2.97	1.35	4.93	4.11	3.34	3.84	18.05	7.79

Table 8: Measurements of Nitrate + Nitrite (mg N/L)

Stormwater Type	Average Stormwater					Metal Spike	Nutrient Spike	After Drought
Date	7/7/14	7/21/14	8/4/14	8/18/14	Average	9/1/14	9/22/14	10/7/14
BL2-S	1.29	1.23	1.42	1.32	1.31	1.42	1.01	0.56
BL4-S	0.30	0.91	0.94	1.08	0.81	0.94	0.94	0.56
BM2-S	1.16	1.00	1.06	1.22	1.11	1.17	1.13	1.24
BM4-S	1.08	1.06	1.02	1.40	1.14	1.69	1.39	1.23
AG1-S	0.24	0.21	0.28	0.20	0.23	0.33	0.27	0.28
AG3-S	0.13	0.17	0.99	0.34	0.41	0.30	0.31	0.30
RO1-S	0.10	0.46	0.64	0.53	0.43	0.47	0.44	0.43
RO3-S	0.31	0.27	0.38	0.61	0.39	0.49	0.50	0.45
CS2-S	0.34	0.44	1.06	0.59	0.61	0.65	0.76	1.05
CS4-S	0.81	0.73	0.70	0.94	0.79	0.63	0.74	0.71
PM1-S	0.67	0.45	0.36	0.47	0.49	0.43	0.41	0.32
PM3-S	0.70	0.51	0.51	0.52	0.56	0.49	0.43	0.30
SW1-S	0.37	0.22	1.01	0.46	0.52	0.43	0.60	0.71
SW4-S	0.24	0.24	0.44	0.25	0.29	0.35	1.11	0.78
IG1-S	0.56	0.50	0.71	0.56	0.58	0.57	0.68	1.17
IG4-S	0.42	0.24	0.24	0.22	0.28	0.36	0.36	0.36
IGA2-S	0.77	0.42	0.74	0.52	0.61	0.51	0.52	0.39
IGA3-S	1.16	0.44	0.98	0.62	0.80	0.37	0.57	0.39
BL1	3.52	2.58	2.18	2.61	2.72	2.52	2.03	2.66
BL3	3.32	2.59	1.87	2.38	2.54	2.45	1.89	3.62
BM1	1.87	1.95	2.15	2.48	2.11	3.05	2.19	3.43
BM3	3.50	2.30	1.92	2.96	2.67	2.57	2.76	3.94
AG2	0.88	0.66	0.79	0.84	0.80	0.68	0.70	0.48
AG4	1.38	1.90	1.87	1.93	1.77	1.66	1.44	1.34
RO2	2.16	0.94	1.59	1.80	1.62	2.57	1.17	0.97
RO4	1.38	0.72	1.02	1.83	1.23	1.02	1.51	0.77
CS1	2.59	1.81	1.70	1.57	1.92	0.01	1.28	0.91
CS3	1.27	0.85	1.16	1.69	1.24	0.84	6.21	2.72
PM2	2.00	2.23	1.46	1.39	1.77	1.02	1.00	0.84
PM4	1.58	1.78	1.14	1.52	1.51	1.41	1.46	1.32
SW2	0.95	0.65	1.07	0.89	0.89	0.82	1.08	0.97
SW3	0.89	0.73	0.74	0.81	0.79	0.84	1.84	1.91
IG2	3.05	1.68	1.32	1.66	1.93	1.24	3.26	0.87
IG3	2.09	1.15	1.47	1.46	1.54	0.77	1.11	1.83
IG-A1	0.52	0.36	0.29	0.39	0.39	0.47	0.65	0.45

Table 9: Measurements of Ammonium (mg N/L)

Stormwater Type	Average Stormwater					Metal Spike	Nutrient Spike	After Drought
Date	7/7/14	7/21/14	8/4/14	8/18/14	Average	9/1/14	9/22/14	10/7/14
BL2-S	0.94	0.63	0.62	0.73	0.73	0.49	0.99	1.29
BL4-S	0.74	0.74	0.71	0.57	0.69	0.73	1.13	1.31
BM2-S	1.40	1.63	1.48	1.34	1.46	1.71	2.31	2.41
BM4-S	1.25	1.32	1.30	1.47	1.34	1.43	2.36	2.78
AG1-S	0.59	0.84	0.78	0.84	0.76	0.85	0.67	1.11
AG3-S	0.78	0.58	0.89	1.06	0.83	0.81	1.06	1.23
RO1-S	0.82	1.31	1.66	1.17	1.24	1.24	1.44	1.32
RO3-S	0.72	1.09	1.22	1.83	1.21	1.49	1.63	2.21
CS2-S	1.10	1.09	0.21	1.21	0.90	1.11	2.06	1.61
CS4-S	1.30	0.86	0.94	1.00	1.02	1.08	1.74	2.19
PM1-S	0.95	1.07	1.34	1.22	1.14	1.13	1.42	1.53
PM3-S	0.88	1.05	0.83	1.03	0.95	1.08	1.44	1.59
SW1-S	0.77	0.21	1.42	0.90	0.83	0.22	1.00	0.66
SW4-S	0.51	0.31	1.11	0.36	0.57	0.27	1.90	0.49
IG1-S	0.99	0.78	1.27	1.16	1.05	0.88	1.27	1.69
IG4-S	1.02	0.69	0.86	0.92	0.87	0.51	0.97	1.18
IGA2-S	0.74	0.32	0.24	0.28	0.40	0.14	0.18	0.76
IGA3-S	0.89	0.22	0.39	0.48	0.50	0.38	0.83	0.06
BL1	0.21	0.48	0.35	0.32	0.34	0.26	1.22	0.29
BL3	0.63	0.55	0.33	0.44	0.49	0.49	0.87	0.15
BM1	0.67	0.34	0.39	0.71	0.53	1.01	1.44	0.46
BM3	0.83	0.38	0.24	0.61	0.51	0.66	1.31	0.44
AG2	0.63	0.26	0.30	0.45	0.41	1.06	0.87	0.34
AG4	0.68	0.26	0.59	0.50	0.50	0.52	1.33	0.44
RO2	1.15	0.20	0.37	0.27	0.50	0.68	1.52	0.57
RO4	1.18	0.39	0.20	0.40	0.54	0.34	1.28	0.45
CS1	1.08	0.46	0.50	0.40	0.61	0.61	0.71	0.81
CS3	0.86	0.43	2.84	0.73	1.22	0.40	5.00	0.43
PM2	0.75	0.41	0.41	0.38	0.49	0.62	1.35	0.64
PM4	0.73	0.30	0.32	0.29	0.41	0.50	0.97	0.51
SW2	0.64	0.23	0.58	0.43	0.47	0.44	0.85	0.50
SW3	0.79	0.29	0.31	0.53	0.48	0.66	0.72	0.51
IG2	1.53	0.49	0.58	0.58	0.79	0.56	2.35	0.57
IG3	1.27	0.76	0.86	0.77	0.92	0.87	0.96	0.55
IG-A1	1.04	0.30	0.53	0.31	0.55	1.24	0.81	0.22

Table 10: Measurements of Organic Nitrogen (Total Nitrogen minus Ammonium, Nitrate, and Nitrite) (mg N/L)

Stormwater Type	Average Stormwater					Metal Spike	Nutrient Spike	After Drought
Date	7/7/14	7/21/14	8/4/14	8/18/14	Average	9/1/14	9/22/14	10/7/14
BL2-S	n.d.	1.94	4.37	13.43	6.58	10.78	24.67	10.10
BL4-S	0.77	1.50	2.64	11.99	4.23	7.65	8.52	13.48
BM2-S	3.91	3.70	2.93	10.99	5.38	11.07	13.73	16.40
BM4-S	3.50	n.d	n.d	11.57	7.53	14.37	18.12	16.09
AG1-S	1.10	0.37	0.70	1.47	0.91	8.22	8.09	5.57
AG3-S	0.24	0.68	2.50	2.59	1.50	3.74	8.19	5.34
RO1-S	0.82	2.99	6.37	4.98	3.79	3.24	5.97	6.99
RO3-S	1.75	4.06	5.81	5.69	4.33	5.76	12.81	6.14
CS2-S	1.27	3.54	5.31	5.03	3.79	6.03	11.85	10.82
CS4-S	2.51	2.95	3.18	7.30	3.98	10.59	11.04	9.74
PM1-S	2.05	5.61	5.36	3.76	4.20	5.27	8.89	0.36
PM3-S	2.04	1.98	5.85	3.45	3.33	5.82	8.21	6.22
SW1-S	1.42	2.17	-0.09	5.99	2.37	3.62	10.98	1.44
SW4-S	0.98	5.67	4.40	1.79	3.21	5.16	15.50	1.49
IG1-S	2.56	n.d	0.57	4.02	2.39	3.69	11.18	6.47
IG4-S	1.12	1.08	3.38	1.57	1.79	3.96	10.04	0.20
IGA2-S	n.d.	1.96	4.93	3.34	3.41	5.06	11.63	6.26
IGA3-S	n.d.	5.38	4.57	4.49	4.81	11.16	11.85	6.12
BL1	11.08	n.d	1.52	22.19	11.60	17.17	24.06	19.02
BL3	9.96	n.d	0.72	20.36	10.35	18.29	4.05	30.13
BM1	5.96	0.22	2.42	21.16	7.44	14.77	26.69	23.66
BM3	10.16	1.81	4.26	20.55	9.19	70.59	28.93	26.12
AG2	3.43	1.90	5.22	6.17	4.18	5.91	14.93	0.71
AG4	4.47	6.50	4.73	20.81	9.13	12.80	17.79	12.83
RO2	6.37	9.76	3.59	16.19	8.98	9.66	19.35	7.87
RO4	4.16	9.90	3.97	11.69	7.43	11.13	22.24	6.78
CS1	7.34	4.50	7.72	10.53	7.52	20.35	19.11	5.17
CS3	3.94	9.27	4.98	11.32	7.38	7.06	54.97	19.65
PM2	5.95	-0.01	2.37	10.07	4.59	15.27	16.70	6.87
PM4	4.91	1.32	4.12	14.40	6.19	16.99	19.76	12.90
SW2	3.30	7.27	5.63	5.99	5.55	15.55	17.17	11.05
SW3	3.06	1.48	3.63	5.40	3.39	14.79	22.50	16.88
IG2	7.98	n.d.	n.d.	10.80	9.39	n.d.	32.33	9.95
IG3	6.17	0.14	1.70	10.08	4.52	2.16	19.13	9.19
IG-A1	1.41	0.69	4.10	3.41	2.40	2.13	16.59	7.12

Table 11: Measurements of Copper (mg/L)

Stormwater Type	Average Stormwater					Metal Spike	Nutrient Spike	After Drought
Date	7/7/14	7/21/14	8/4/14	8/18/14	Average	9/1/14	9/22/14	10/7/14
BL2-S	0.003	n.d.	0.002	n.d.	0.003	n.d.	n.d.	n.d.
BL4-S	0.001	n.d.	n.d.	n.d.	0.001	n.d.	n.d.	n.d.
BM2-S	0.002	n.d.	n.d.	n.d.	0.002	0.000	n.d.	n.d.
BM4-S	0.002	n.d.	n.d.	n.d.	0.002	n.d.	n.d.	n.d.
AG1-S	0.023	n.d.	n.d.	n.d.	0.023	0.001	n.d.	0.004
AG3-S	0.001	n.d.	0.001	n.d.	0.001	n.d.	n.d.	0.002
RO1-S	n.d.	n.d.	n.d.	n.d.	n.d.	0.001	n.d.	0.008
RO3-S	0.002	n.d.	n.d.	n.d.	0.002	n.d.	n.d.	0.001
CS2-S	n.d.	n.d.	0.011	n.d.	0.011	n.d.	n.d.	0.005
CS4-S	0.005	0.001	n.d.	n.d.	0.003	0.000	n.d.	0.001
PM1-S	0.006	n.d.	n.d.	n.d.	0.006	n.d.	n.d.	0.001
PM3-S	0.002	n.d.	0.001	n.d.	0.002	n.d.	n.d.	0.000
SW1-S	0.002	n.d.	0.001	n.d.	0.002	0.000	n.d.	0.004
SW4-S	0.001	n.d.	n.d.	n.d.	0.001	0.000	n.d.	0.003
IG1-S	0.002	n.d.	n.d.	n.d.	0.002	n.d.	n.d.	0.003
IG4-S	0.002	n.d.	n.d.	n.d.	0.002	0.000	n.d.	0.006
IGA2-S	0.002	n.d.	n.d.	n.d.	0.002	0.000	n.d.	0.003
IGA3-S	0.001	n.d.	0.002	n.d.	0.002	n.d.	n.d.	0.003
BL1	0.007	0.006	0.007	0.006	0.007	0.006	0.003	0.008
BL3	0.006	0.005	0.006	0.007	0.006	0.006	0.009	0.007
BM1	0.007	0.006	0.006	0.008	0.007	0.007	0.010	0.009
BM3	0.006	0.006	0.008	0.009	0.007	0.007	0.009	0.009
AG2	0.013	0.010	0.008	0.008	0.010	0.008	0.013	0.010
AG4	0.009	0.005	0.010	0.009	0.008	0.006	0.014	0.009
RO2	0.017	0.009	0.010	0.009	0.011	0.009	0.012	0.009
RO4	0.012	0.006	0.011	0.012	0.010	0.008	0.014	0.010
CS1	0.009	0.006	0.010	0.008	0.008	0.008	0.018	0.009
CS3	0.007	0.007	n.d.	0.010	0.008	0.007	0.022	0.018
PM2	0.008	0.008	0.009	0.009	0.009	0.008	0.012	0.008
PM4	0.009	0.007	0.010	0.011	0.009	0.010	0.016	0.011
SW2	0.013	0.010	0.013	0.011	0.012	0.007	0.012	0.013
SW3	0.010	0.008	0.009	0.009	0.009	0.004	0.014	0.011
IG2	0.014	0.011	0.009	0.011	0.011	0.007	0.020	0.012
IG3	0.009	0.004	0.007	0.007	0.007	0.004	0.009	0.009
IG-A1	0.004	0.002	0.005	0.007	0.005	0.006	0.009	0.013

Table 12: Measurements of Lead (mg/L)

Stormwater Type	Average Stormwater					Metal Spike	Nutrient Spike	After Drought
Date	7/7/14	7/21/14	8/4/14	8/18/14	Average	9/1/14	9/22/14	10/7/14
BL2-S	0.002	0.001	0.013	0.006	0.006	0.005	0.007	0.001
BL4-S	0.002	n.d.	n.d.	0.007	0.005	0.005	0.007	0.001
BM2-S	n.d.	n.d.	0.002	n.d.	0.002	0.005	0.004	n.d.
BM4-S	n.d.	0.013	0.001	0.008	0.007	0.005	0.003	n.d.
AG1-S	n.d.	n.d.	n.d.	n.d.	n.d.	0.010	0.005	n.d.
AG3-S	0.002	n.d.	0.007	n.d.	0.005	0.006	0.003	n.d.
RO1-S	0.002	n.d.	0.001	n.d.	0.002	0.007	n.d.	0.003
RO3-S	n.d.	n.d.	n.d.	n.d.	n.d.	0.002	0.000	n.d.
CS2-S	n.d.	0.003	0.018	n.d.	0.011	0.009	0.006	0.004
CS4-S	n.d.	0.002	0.003	n.d.	0.003	0.008	0.003	0.001
PM1-S	n.d.	n.d.	0.006	n.d.	0.006	0.006	0.005	n.d.
PM3-S	0.001	n.d.	n.d.	n.d.	0.001	0.006	0.004	n.d.
SW1-S	n.d.	n.d.	0.005	n.d.	0.005	0.004	0.005	0.002
SW4-S	n.d.	n.d.	0.012	n.d.	0.012	0.006	0.004	0.001
IG1-S	0.001	n.d.	0.001	0.007	0.003	0.003	0.002	n.d.
IG4-S	0.001	n.d.	n.d.	0.005	0.003	0.005	0.013	0.001
IGA2-S	0.004	n.d.	0.005	0.008	0.006	0.007	0.018	0.002
IGA3-S	n.d.	0.001	0.004	0.003	0.003	0.006	0.017	0.001
BL1	n.d.	0.001	0.016	0.005	0.007	0.013	0.013	0.002
BL3	n.d.	0.003	0.001	0.007	0.004	0.007	0.004	n.d.
BM1	0.003	n.d.	0.005	0.008	0.005	0.008	0.008	0.001
BM3	0.004	0.004	0.001	0.001	0.003	0.007	0.008	n.d.
AG2	n.d.	0.002	0.003	0.001	0.002	0.010	0.006	0.003
AG4	0.003	0.004	0.005	n.d.	0.004	0.011	0.006	0.002
RO2	0.002	0.003	0.004	n.d.	0.003	0.010	0.004	n.d.
RO4	0.001	n.d.	0.005	0.001	0.002	0.008	0.007	n.d.
CS1	0.002	0.008	0.003	0.001	0.004	0.010	0.006	n.d.
CS3	0.002	0.002	0.009	n.d.	0.004	0.009	0.011	0.005
PM2	0.001	0.002	0.006	n.d.	0.003	0.012	0.004	n.d.
PM4	n.d.	0.003	0.002	n.d.	0.003	0.007	0.004	0.001
SW2	0.003	0.002	0.008	0.001	0.004	0.008	0.004	0.002
SW3	0.002	0.001	0.005	n.d.	0.003	0.012	0.002	n.d.
IG2	0.002	0.011	n.d.	0.006	0.006	0.009	0.005	n.d.
IG3	0.002	n.d.	0.004	0.005	0.004	0.006	0.005	n.d.
IG-A1	n.d.	n.d.	0.001	0.007	0.004	0.009	0.004	n.d.

Table 13: Measurements of Zinc (mg/L)

Stormwater Type	Average Stormwater					Metal Spike	Nutrient Spike	After Drought
Date	7/7/14	7/21/14	8/4/14	8/18/14	Average	9/1/14	9/22/14	10/7/14
BL2-S	0.026	0.066	0.094	0.043	0.057	0.028	0.140	0.258
BL4-S	0.030	0.059	0.014	0.111	0.053	0.043	0.136	0.198
BM2-S	0.019	0.050	0.119	0.022	0.053	0.018	0.063	0.062
BM4-S	0.027	0.073	0.041	0.019	0.040	0.062	0.081	0.100
AG1-S	0.009	0.069	0.059	0.041	0.045	0.048	0.215	0.104
AG3-S	n.d.	0.035	0.072	0.065	0.057	0.034	0.054	0.074
RO1-S	0.004	0.062	0.041	0.034	0.035	0.020	0.042	0.154
RO3-S	n.d.	0.052	0.020	0.024	0.032	0.020	0.065	0.054
CS2-S	n.d.	0.099	0.067	0.054	0.073	0.023	0.074	0.059
CS4-S	0.007	0.060	0.082	0.051	0.050	0.032	0.016	0.029
PM1-S	0.029	0.057	0.070	0.014	0.043	0.032	0.027	0.016
PM3-S	0.021	0.049	0.061	0.023	0.039	0.025	0.025	0.057
SW1-S	0.024	0.074	0.083	0.032	0.053	0.145	0.167	n.d.
SW4-S	0.011	0.078	0.052	0.070	0.053	0.034	0.097	0.100
IG1-S	0.012	0.059	0.051	0.078	0.050	0.036	0.094	0.044
IG4-S	0.006	0.041	0.032	0.047	0.032	0.053	0.057	n.d.
IGA2-S	0.066	0.078	0.101	0.053	0.075	0.040	0.071	0.040
IGA3-S	0.098	0.095	0.089	0.095	0.094	0.030	0.230	0.023
BL1	0.042	0.120	0.081	0.082	0.081	0.061	0.198	0.243
BL3	0.054	0.097	0.072	0.100	0.081	0.054	0.252	0.245
BM1	0.032	0.090	0.088	0.057	0.067	0.096	0.259	0.134
BM3	0.044	0.078	0.086	0.063	0.068	0.073	0.136	0.150
AG2	0.036	0.073	0.069	0.058	0.059	0.041	0.096	0.051
AG4	0.028	0.092	0.091	0.081	0.073	0.055	0.208	0.069
RO2	0.062	0.103	0.109	0.255	0.132	0.046	0.098	0.060
RO4	0.038	0.085	0.043	0.061	0.057	0.053	0.069	0.058
CS1	0.034	0.118	0.113	0.102	0.092	0.059	0.049	0.015
CS3	0.011	0.060	0.081	0.056	0.052	0.045	0.156	0.087
PM2	0.050	0.136	0.167	0.073	0.107	0.058	0.033	0.256
PM4	0.119	0.204	0.230	0.188	0.185	0.136	0.120	0.214
SW2	0.044	0.080	0.068	0.057	0.062	0.044	0.084	n.d.
SW3	0.026	0.093	0.058	0.047	0.056	0.110	0.100	0.289
IG2	0.045	0.119	0.068	0.064	0.074	0.092	0.158	0.098
IG3	0.046	0.129	0.107	0.081	0.091	0.095	0.263	0.032
IG-A1	0.145	0.091	0.057	0.075	0.092	0.040	0.063	0.080

Table 14: Measurements of Turbidity (NTU)

Stormwater Type	Average Stormwater				Metal Spike	Nutrient Spike	After Drought
Date	7/21/14	8/4/14	8/18/14	Average	9/1/14	9/22/14	10/7/14
BL2-S	18.12	13.18	17.60	16.30	21.66	29.93	19.06
BL4-S	20.32	22.95	21.52	21.60	17.60	22.73	15.41
BM2-S	24.02	11.71	24.61	20.11	19.10	16.89	34.57
BM4-S	24.92	12.97	25.91	21.27	15.74	26.54	28.46
AG1-S	39.73	40.99	44.96	41.89	40.75	23.81	47.75
AG3-S	38.48	22.22	26.91	29.20	30.95	27.89	50.03
RO1-S	43.19	22.28	28.38	31.28	49.99	50.52	76.55
RO3-S	36.03	17.92	18.28	24.08	13.02	22.83	58.84
CS2-S	30.03	13.97	21.25	21.75	23.23	23.26	52.71
CS4-S	16.57	14.96	18.95	16.83	15.11	17.96	33.91
PM1-S	37.89	21.67	31.70	30.42	23.88	52.22	49.95
PM3-S	30.32	18.98	30.04	26.45	26.52	56.24	51.40
SW1-S	46.57	33.43	36.66	38.89	33.25	45.58	48.95
SW4-S	46.74	38.60	40.77	42.04	36.09	22.89	32.27
IG1-S	26.74	31.28	30.75	29.59	26.02	24.94	39.54
IG4-S	46.21	48.51	44.04	46.25	44.05	32.18	100.40
IGA2-S	1.88	0.76	2.19	1.61	1.55	1.76	15.12
IGA3-S	7.56	7.58	5.67	6.94	5.50	4.12	24.92
BL1	34.04	22.15	24.74	26.98	23.16	31.07	36.24
BL3	23.88	22.67	37.31	27.95	29.19	39.75	30.48
BM1	26.85	17.29	26.21	23.45	25.65	27.50	28.19
BM3	27.06	21.08	26.75	24.96	28.42	31.80	31.05
AG2	66.13	47.78	64.61	59.51	72.02	61.31	224.80
AG4	39.47	29.29	57.82	42.19	47.92	58.70	68.45
RO2	84.43	50.29	66.42	67.05	59.02	73.53	124.30
RO4	68.85	47.84	47.01	54.57	46.62	55.32	170.70
CS1	42.86	33.43	47.81	41.37	48.72	56.99	108.10
CS3	75.51	56.58	45.68	59.26	86.20	34.68	55.33
PM2	23.08	24.66	44.77	30.84	47.53	72.50	132.10
PM4	36.57	31.71	40.50	36.26	40.08	56.51	104.50
SW2	80.48	45.71	75.02	67.07	77.57	57.88	122.40
SW3	85.40	55.28	70.74	70.47	58.75	67.92	88.60
IG2	41.25	36.49	44.74	40.83	54.58	28.98	67.49
IG3	60.28	35.61	46.52	47.47	42.79	52.56	77.84
IG-A1	15.55	27.10	50.38	31.01	19.19	18.81	7.16

Table 15: Measurements of pH

Stormwater Type	Average Stormwater				Metal Spike	Nutrient Spike	After Drought
Date	7/21/14	8/4/14	8/18/14	Average	9/1/14	9/22/14	10/7/14
BL2-S	6.89	6.53	6.64	6.69	6.45	6.49	6.36
BL4-S	6.87	6.50	6.62	6.66	6.77	6.51	6.30
BM2-S	6.04	6.74	6.80	6.53	6.78	6.60	6.44
BM4-S	6.90	6.66	6.70	6.75	6.66	6.50	6.58
AG1-S	6.72	6.48	6.62	6.61	6.57	6.38	6.36
AG3-S	6.56	6.52	6.58	6.55	6.48	6.57	6.51
RO1-S	6.85	6.70	6.58	6.71	6.61	6.49	6.47
RO3-S	6.90	6.59	6.62	6.70	6.54	6.72	6.32
CS2-S	6.87	6.62	6.60	6.70	6.58	6.69	6.65
CS4-S	6.88	6.70	6.61	7.40	6.64	6.46	6.44
PM1-S	6.91	6.78	6.58	6.76	6.61	6.72	6.64
PM3-S	6.98	6.69	6.65	6.77	6.65	6.56	6.60
SW1-S	6.84	6.35	6.56	6.58	6.48	6.45	6.40
SW4-S	6.85	6.43	6.50	6.59	6.44	6.40	6.30
IG1-S	6.90	6.46	6.58	6.65	6.51	6.40	6.38
IG4-S	6.82	6.59	6.69	6.70	6.60	6.35	6.64
IGA2-S	7.82	7.34	7.51	7.56	7.33	7.40	7.17
IGA3-S	7.84	7.46	7.73	7.68	7.65	7.50	7.36
BL1	5.90	6.53	6.47	6.30	6.65	6.16	6.38
BL3	6.47	6.50	6.32	6.43	6.48	6.30	6.40
BM1	6.66	6.34	6.35	6.45	6.35	6.19	6.37
BM3	6.53	6.52	6.36	6.47	5.78	6.30	6.15
AG2	6.65	6.60	6.59	6.61	6.17	6.42	6.71
AG4	6.51	6.33	6.24	6.36	6.54	6.32	6.54
RO2	6.84	6.70	6.50	6.68	6.57	6.54	6.58
RO4	6.78	6.60	6.72	6.70	6.40	6.55	6.63
CS1	6.65	6.43	6.49	6.52	6.23	6.60	6.72
CS3	6.80	6.80	6.57	6.72	6.73	6.38	6.53
PM2	6.61	6.64	6.46	6.57	6.60	6.57	6.73
PM4	6.70	6.63	6.57	6.63	6.39	6.44	6.67
SW2	6.88	6.45	6.62	6.65	6.57	6.37	6.68
SW3	6.70	6.53	6.66	6.63	6.51	6.40	6.47
IG2	6.65	6.45	6.31	6.47	6.47	6.15	6.45
IG3	6.72	6.46	6.29	6.49	6.44	6.32	6.62
IG-A1	7.24	6.94	7.21	7.13	7.02	6.92	6.93

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